# Latest developments in top pair production at hadron colliders

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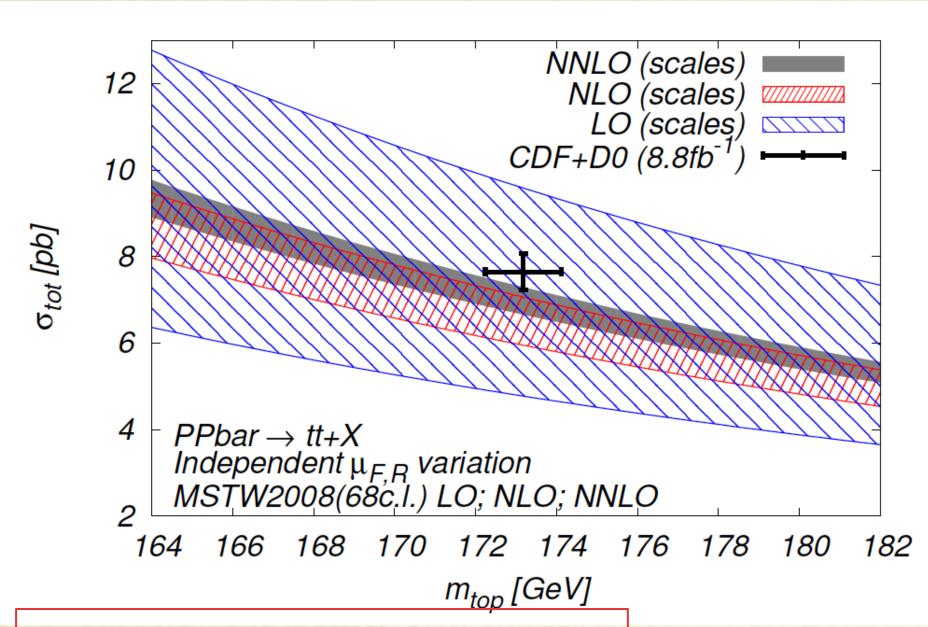
Work with Michael Czakon and Paul Fiedler

## Content of the talk

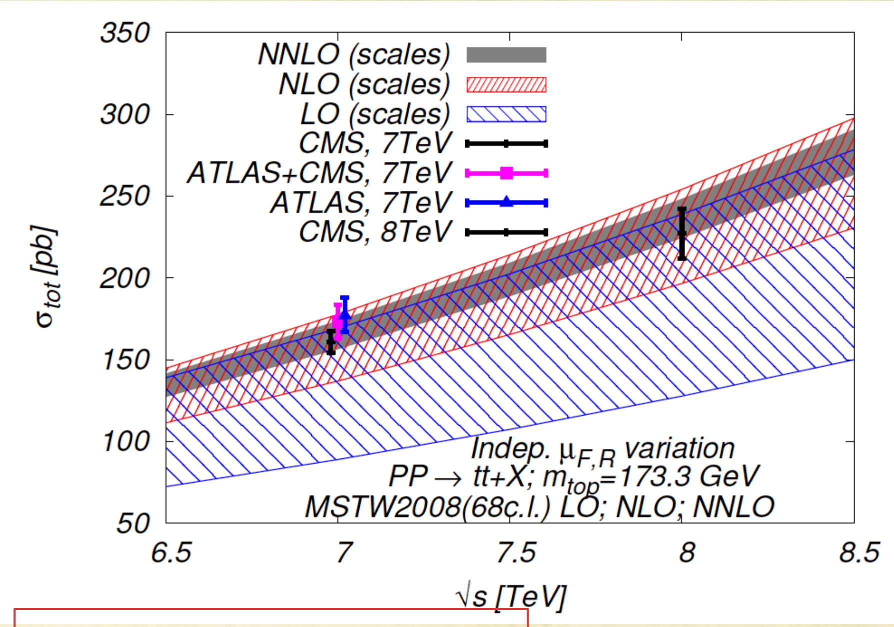
- Precision tt x-sections at hadron colliders: what can we learn about SM and bSM?
- Resolving the $A_{FB}$ puzzle.
- Top quark mass
- Outlook

Good perturbative convergence

✓ Independent F/R scales variation




Scale variation @ Tevatron




Scale variation @ LHC

✓ Good overlap of various orders (LO, NLO, NNLO).

✓ Suggests the (restricted) independent scale variation is a good estimate of missing higher order terms!

This is very important: good control over the perturbative corrections justifies less-conservative overall error estimate, i.e. more predictive theory.

For more detailed comparison, including soft-gluon resummation, see arXiv 1305.3892

## LHC: general features at NNLO+NNLL

Czakon, Fiedler, Mitov '13

Czakon, Mangano, Mitov, Rojo '13

✓ We have reached a point of saturation: uncertainties due to

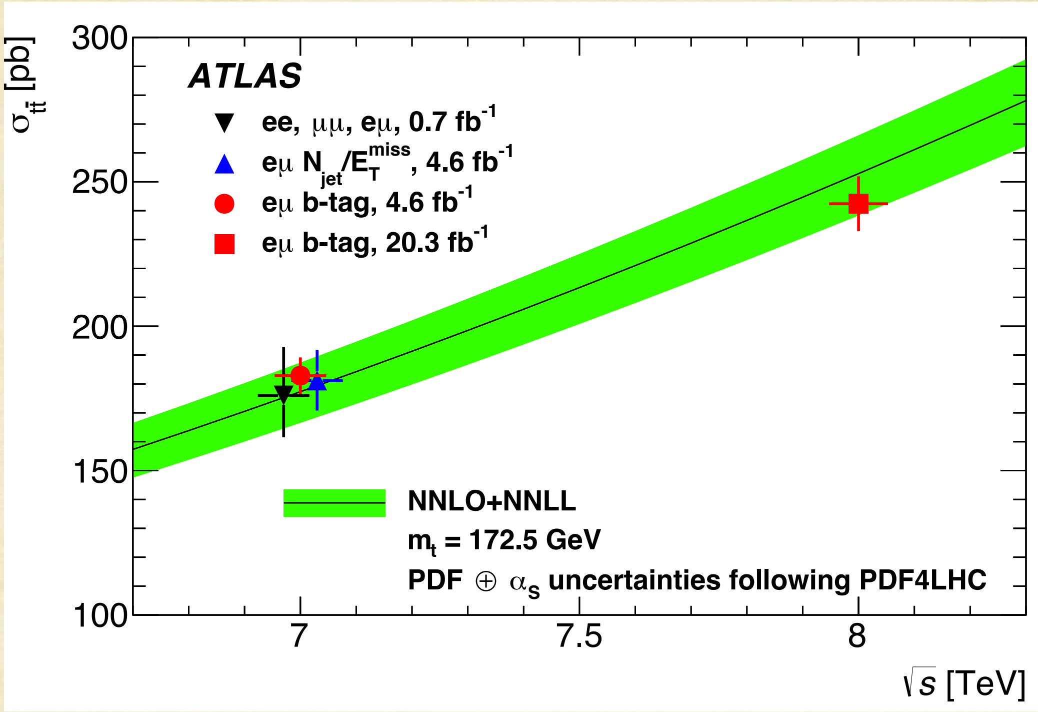
- ✓ scales (i.e. missing yet-higher order corrections) ~ 3%
- ✓ pdf (at 68%cl) ~ 2-3%
- ✓ $alpha_S$ (parametric) ~ 1.5%
- ✓ $m_{top}$ (parametric) ~ 3%

→ All are of similar size!

✓ Soft gluon resummation makes a difference: scale uncertainty 5% → 3%

✓ The total uncertainty tends to decrease when increasing the LHC energy

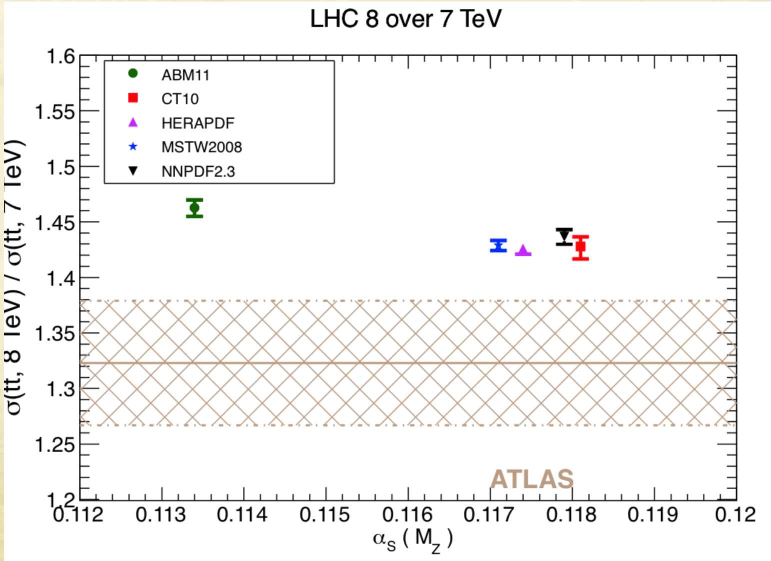
✓ The cross-section agrees well:




ATLAS 1406.5375v2

✓ But the 8TeV/7TeV ratio not so much:

Note: theory errors dramatically cancel in the ratio!

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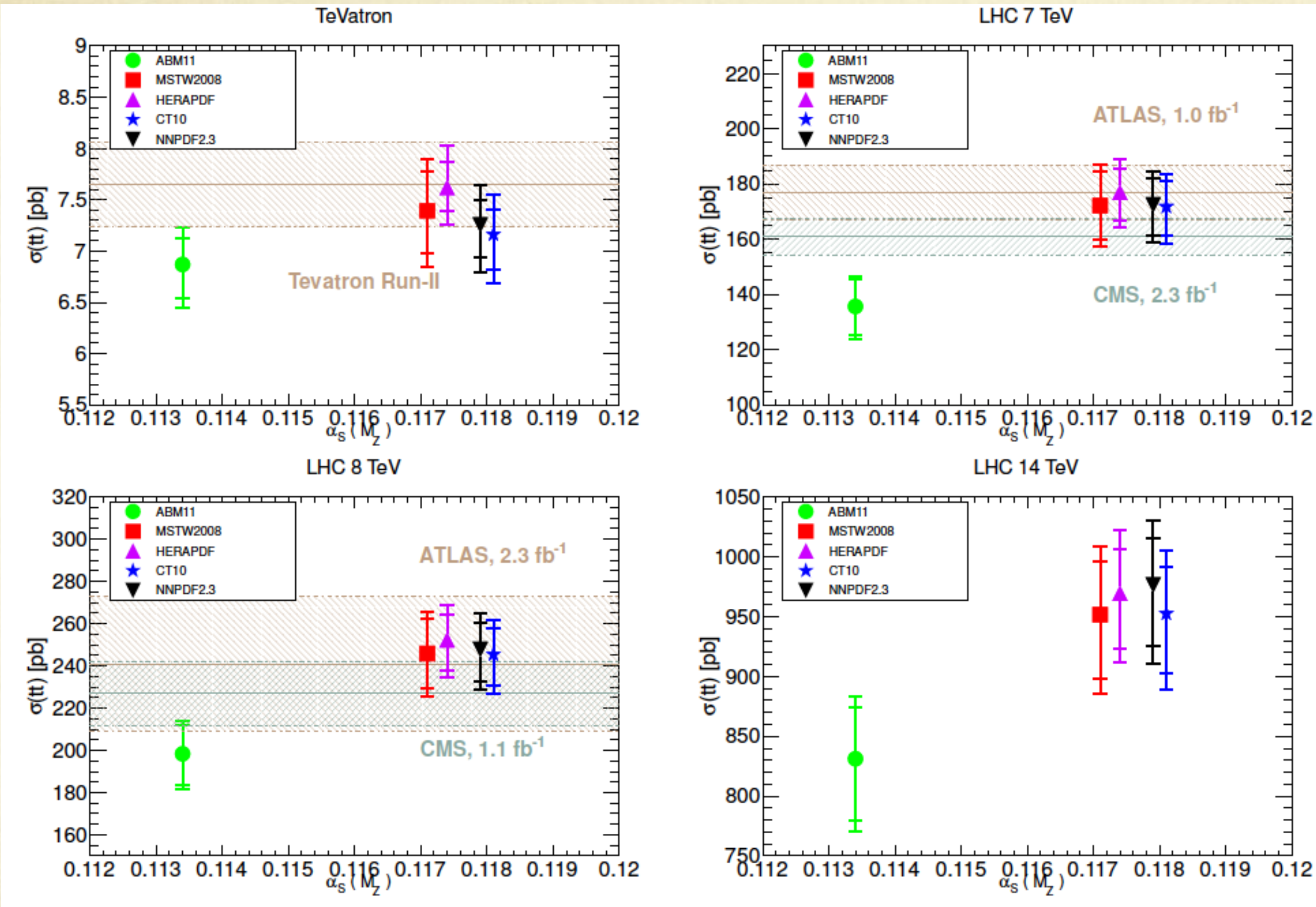
# Application to PDF's

Czakon, Mangano, Mitov, Rojo '13

How existing pdf sets fare when compared to existing data?

Most conservative theory uncertainty:

Scales + pdf + as + mtop




Excellent agreement between almost all pdf sets

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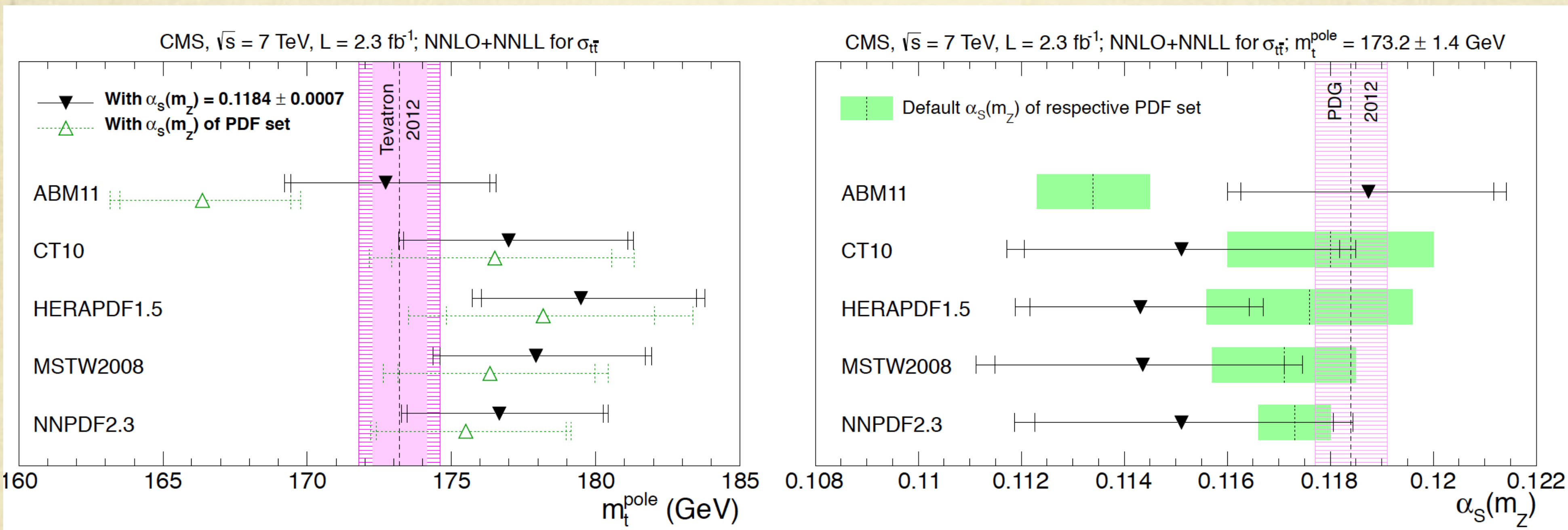
# alpha$_S$ and m$_{TOP}$ extraction from top data (CMS)

How existing pdf sets fare when compared to existing data?

Excellent agreement between almost all pdf sets

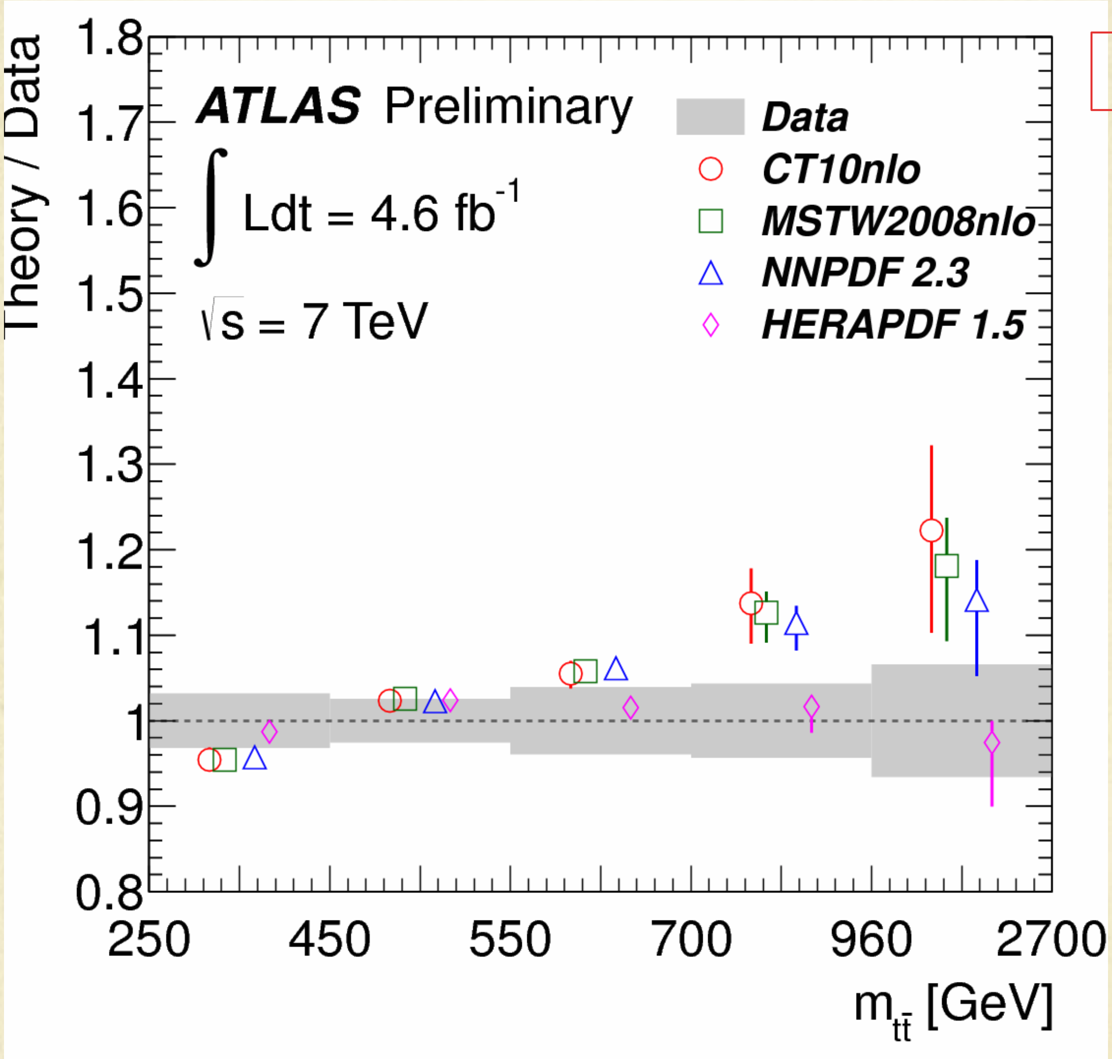
S. Naumann-Emme (CMS) Arxiv:1402.0709




- Results are consistent with world averages, although slight tendency can be seen.
- ABM11 returns value of alpha$_S$ that is incompatible with their assumed value.

# Application to PDF's

How existing pdf sets fare when compared to existing data?




1407.0371

Doesn't look perfect at the differential level (which itself is NLO). Do we have a problem here?

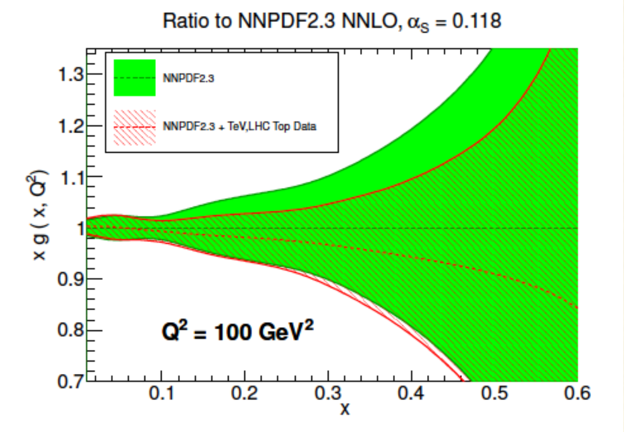
# Application to PDF's

✓ tT offers for the first time a direct NNLO handle to the gluon pdf (at hadron colliders)

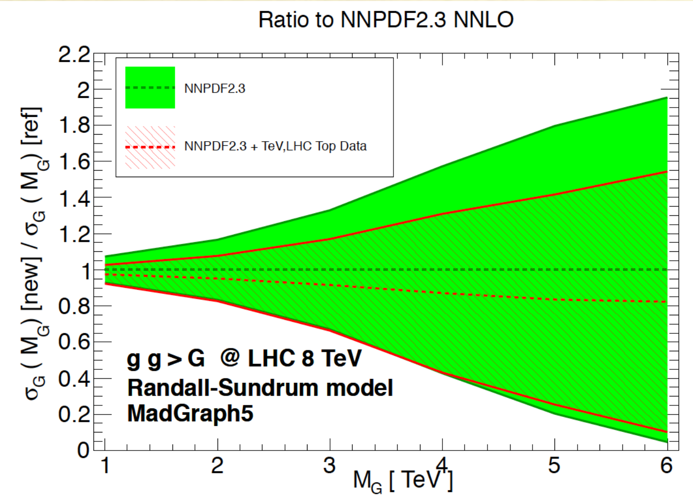
  ✓ implications to many processes at the LHC: Higgs and bSM production at large masses

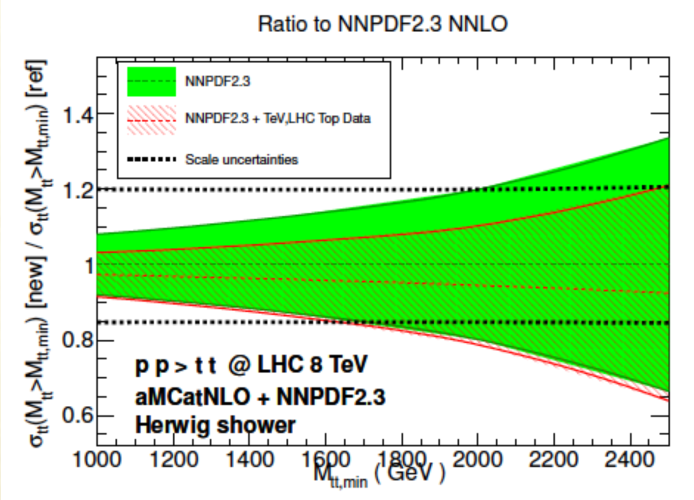
One can use the 5 available (Tevatron/LHC) data-points to improve gluon pdf

"Old" and "new" gluon pdf at large x:




… and PDF uncertainty due to "old" vs. "new" gluon pdf: Czakon, Mangano, Mitov, Rojo '13



# Application to bSM searches: stealthy stop

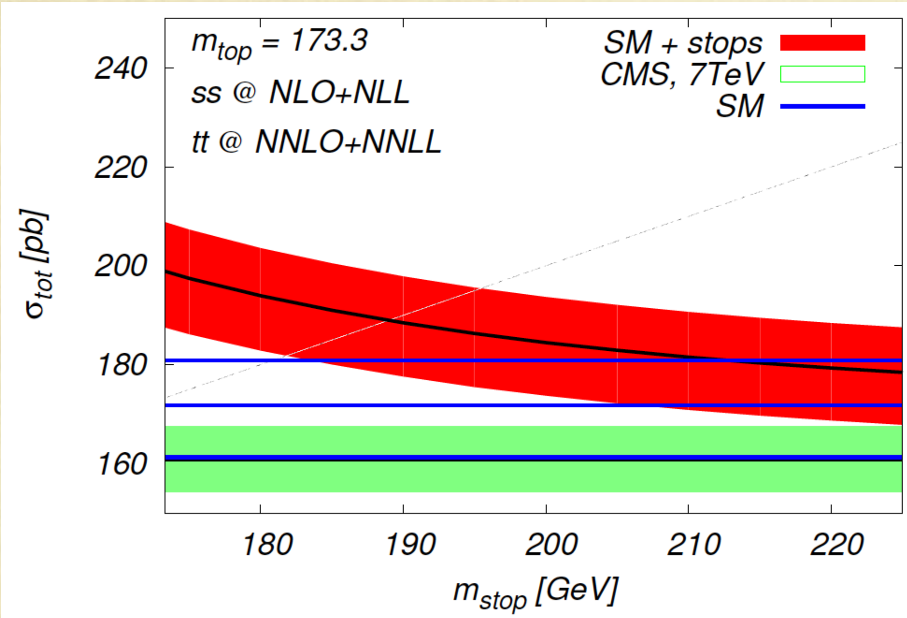
- ✓ Scenario: stop → top + missing energy
  - ✓ m_stop small: just above the top mass.
  - ✓ Usual wisdom: the stop signal hides in the top background

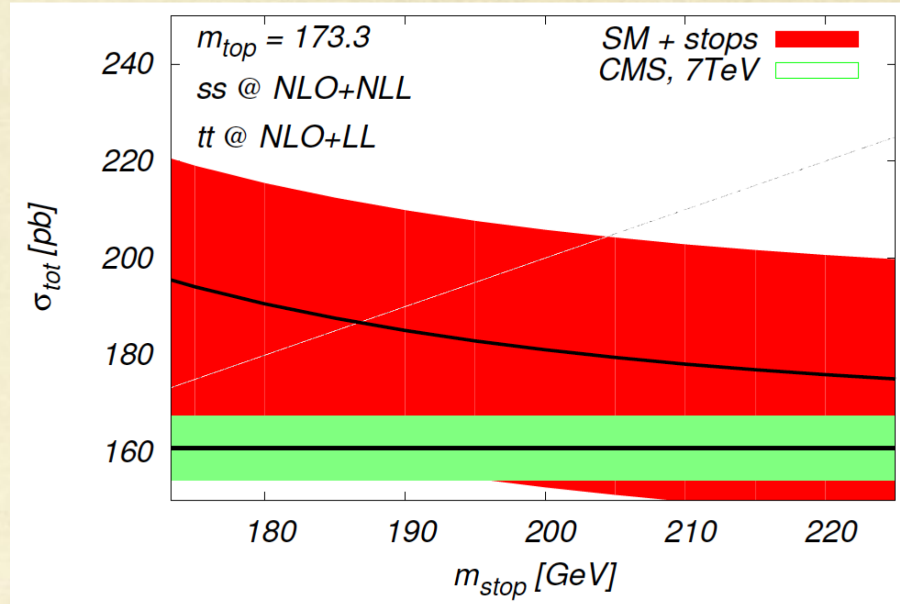
- ✓ The idea: use the top x-section to derive a bound on the stop mass. Assumptions:
  - ✓ Same experimental signature as pure tops
  - ✓ the measured x-section is a sum of top + stop
  - ✓ Use precise predictions for stop production @ NLO+NLL

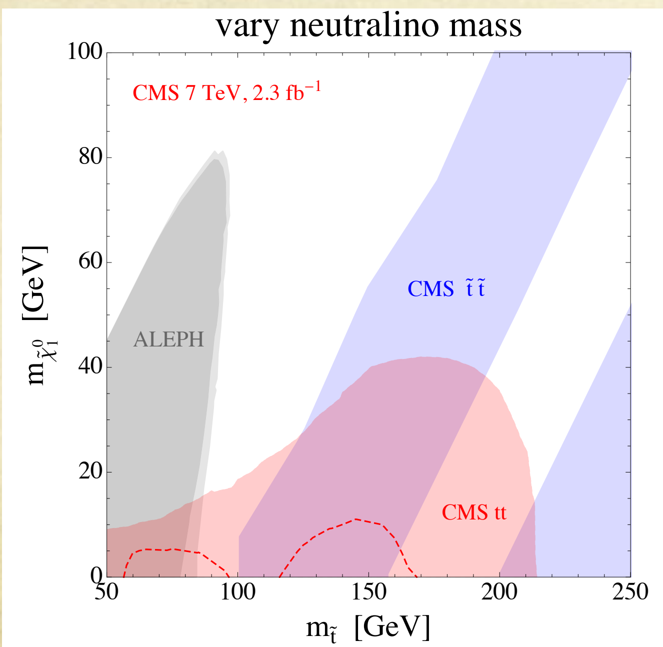
    Krämer, Kulesza, van der Leeuw, Mangano, Padhi, Plehn, Portell `12
  - ✓ Total theory uncertainty: add SM and SUSY ones in quadrature.

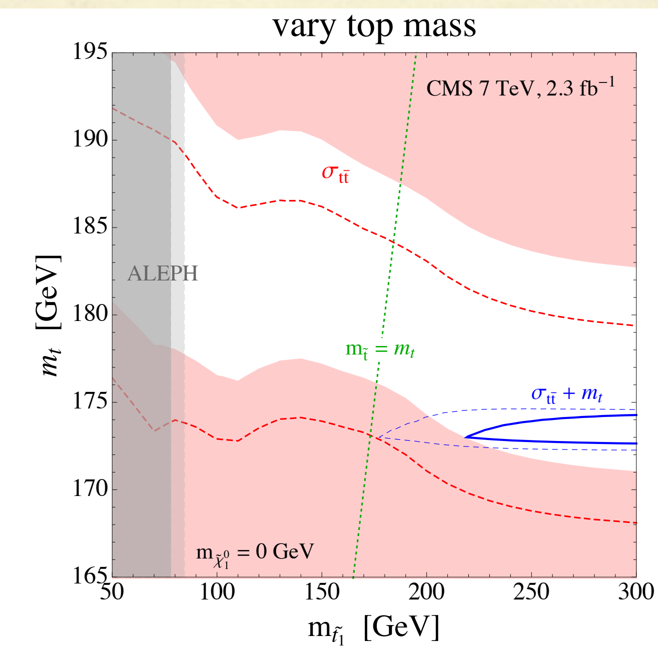
# Applications to the bSM searches: stealth stop

Czakon, Mitov, Papucci, Ruderman, Weiler ’14
ATLAS ’14 (1406.5375)




- Approach is orthogonal to previously used ones
- Improved NNLO accuracy makes all the difference
- Non-trivial exclusion limits possible

The top quark Forward-Backward asymmetry puzzle

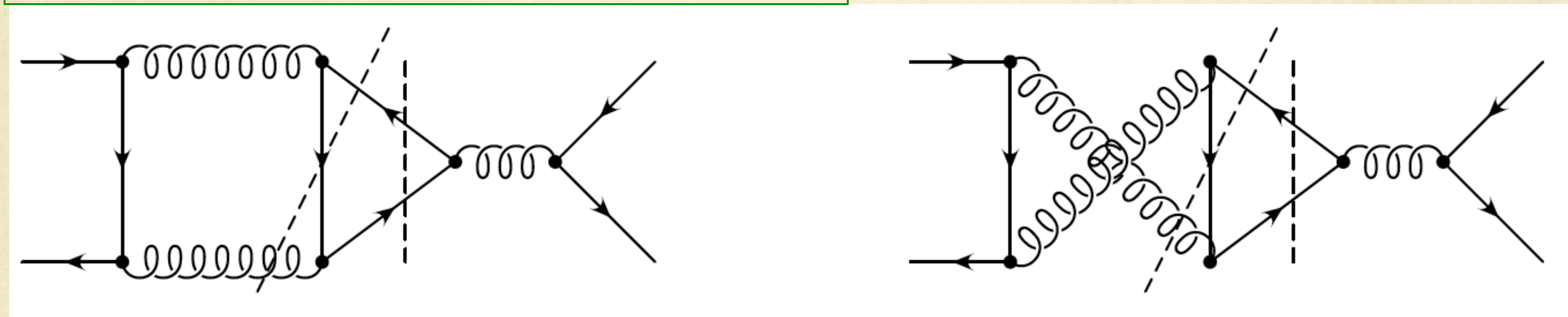
# Introduction: what is $A_{FB}$?

- ✓ At the Tevatron (a P-anti-P collider) top quarks prefer to go in the direction of the proton; antitops in the direction of the antiproton.
- ✓ This asymmetry is known as top quark Forward-Backward Asymmetry (AFB)
- ✓ The asymmetry is predicted in pure QCD (a P and CP conserving theory – as far as we know)
- ✓ Similar asymmetry exists for b-quarks. However its status much more unclear.
- ✓ If all symmetries are conserved, where then does AFB come from?

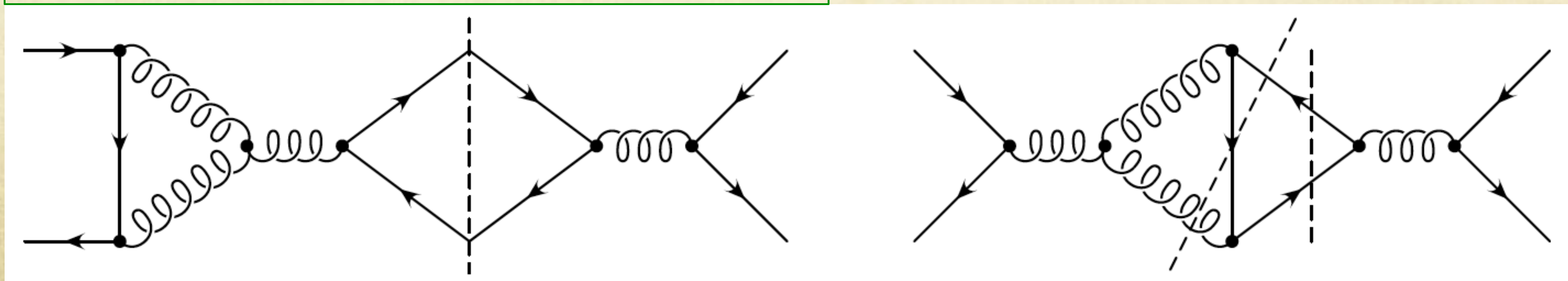
- ✓ AFB is zero at LO QCD for inclusive top pair production. But non-zero at NLO (computed long before the first measurement)

Kuhn, Rodrigo '98

QCD diagrams that generate asymmetry:

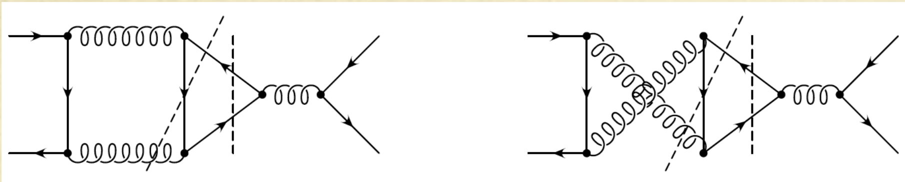


… and some QCD diagrams that do not:

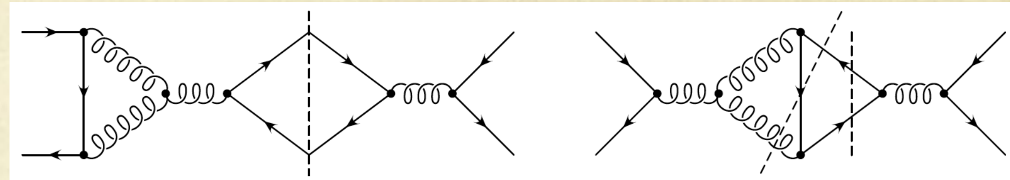


# Introduction: what is $A_{FB}$?

Diagrams that generate asymmetry (type 2)



diagrams that do not (type 1)



✓ What is the origin of AFB?

✓ It turns out one has to look at the Charge conjugation properties of the diagrams when fermions and anti-fermions are exchanged

✓ To appreciate the difference between ABF symmetric and asymmetric diagrams, one has to look at the corresponding vacuum diagrams

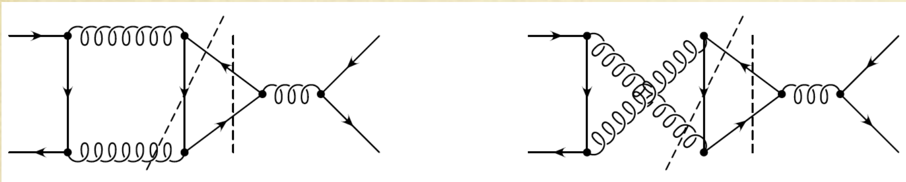
- The diagram as a whole is C even; therefore (at NLO):
    1. a single fermion loop is odd but <u>its associated</u> color charge is also odd
    2. two fermion loops are separately odd and the color charge is even

✓ The AFB generating diagrams are of type 2).

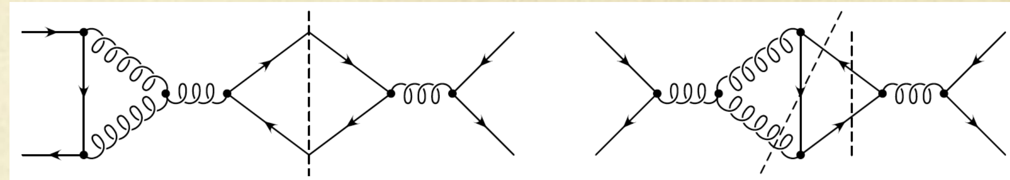
➢ Here is the crucial step:
➢ When we speak of AFB, we are saying: "what happens if we exchange t and t_bar?" (i.e. not the light quarks)
➢ Thus we generate C-odd configuration.
➢ But to survive, it needs something else which is asymmetric otherwise it will get "symmetrized".

# Introduction: what is $A_{FB}$?

QCD diagrams that generate asymmetry:



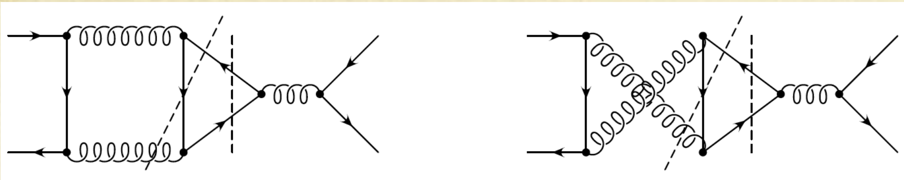
… and some QCD diagrams that do not:



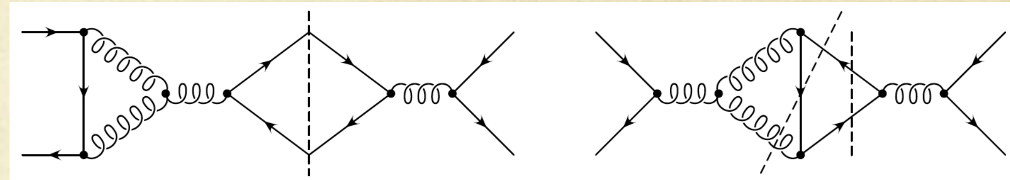
- This is done by the PDF of the proton (not part of these diagrams)
- Due to QCD, <u>and its infinite non-perturbative wisdom</u>, the proton happens to be the ground state of the theory which is stable and has highly asymmetric flavor content (u =/= ubar, etc)
- Therefore, the proton already introduces non-zero asymmetry in the light quarks sector which is then magnified by the top-loop C-asymmetry and we observe this as AFB at Tevatron (or rapidity asymmetry at LHC)
- Indeed, it is well know that gg-initiated states have no AFB (pdf(g) is symmetric…)
- But one can also check (I have) that if we set the pdf's to be symmetric (u=ubar, etc) then AFB=0

# Introduction: what is $A_{FB}$?

QCD diagrams that generate asymmetry:

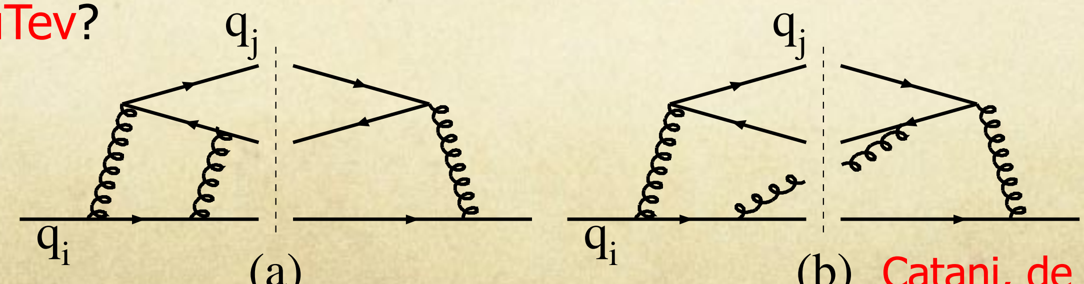


… and some QCD diagrams that do not:



Few more general observations:

- ✓ For ttbar: charge asymmetry starts from NLO
- ✓ For ttbar + jet: starts already from LO
- ✓ Asymmetry appears when sufficiently large number of fermions (real or virtual) are present.
- ✓ The asymmetry is QED like.
- ✓ It does not need massive fermions.
- ✓ Therefore top–like light-jet events (WW+jets) will have AFB as well!
- ✓ It is the twin effect of the perturbative strange (or c- or b-) asymmetry in the proton!
  Remember NuTev?




These diagrams are the same as the ones above !!!

Catani, de Florian, Rodrigo, Vogelsang '04

# How did $A_{FB}$ become what it is today?

✓ I hope I managed to convince you that the physics behind AFB is

- Beautiful
- Rich in features
- Interesting
- Deserving all our attention.

✓ But is this the reason it became so popular?

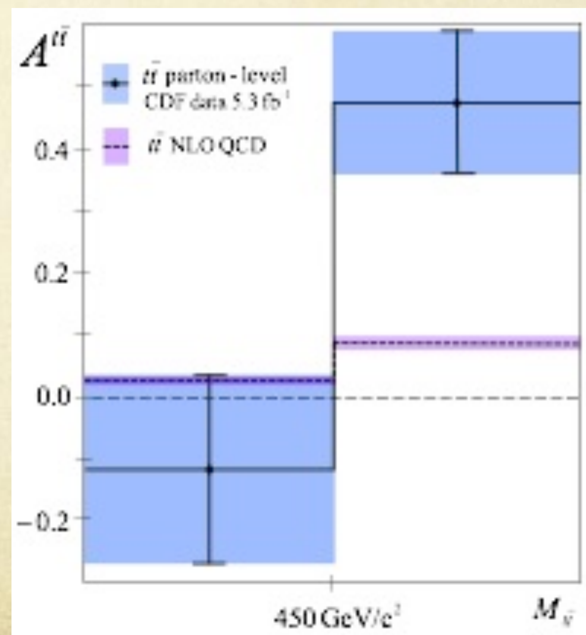
✓ NO!

✓ The reason is this measurement (CDF 2011):

*Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production*

Here is an excerpt from the Abstract:

*Fully corrected parton-level asymmetries are derived in two regions of each variable, and the asymmetry is found to be most significant at large Δy and Mtt. For Mtt ≥ 450 GeV/c², the parton-level asymmetry in the tt rest frame is $A^{tt}$ = 0.475 ± 0.114 compared to a next-to-leading order QCD prediction of 0.088 ± 0.013.*



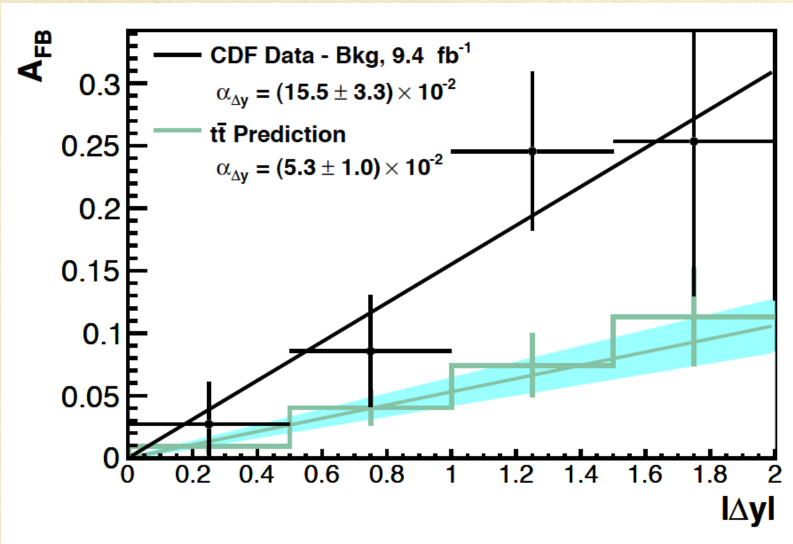

Given the text above and the plot to the right I think it should be obvious why everyone was very excited ☺

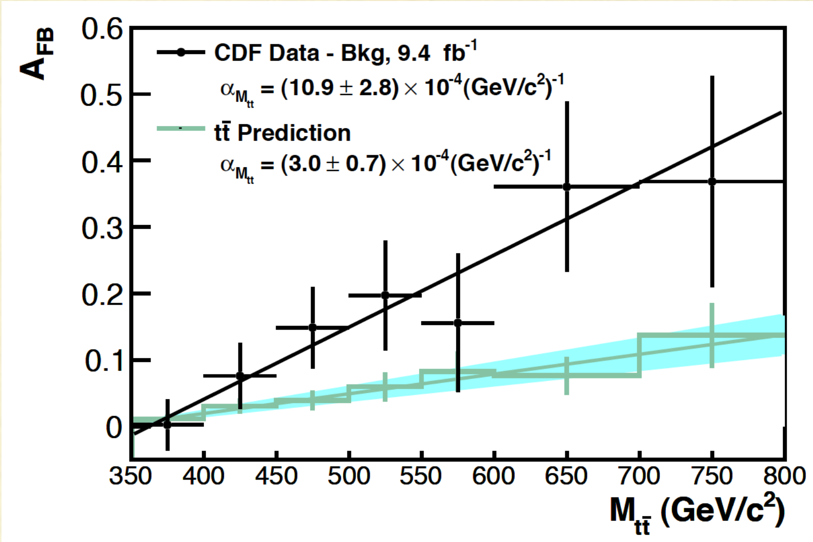
# $A_{FB}$: the current exp status

Definition of the asymmetry:

$$A_{\rm FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

… and the CDF measurement versus (known) SM:




Discrepancy ≤ 3σ

✓ New D0 measurement (2014): it is much lower than CDF and in good agreement with SM

These 2-3 sigma discrepancies defined the field's status for years and generated enormous activity mostly in BSM explanations, but also in refining the SM prediction for AFB

# $A_{FB}$: the status within SM

- ✓ The largest known contribution to $A_{FB}$ is due to NLO QCD, i.e. $\sim(\alpha_S)^3$.

  Kuhn, Rodrigo '98

- ✓ Higher order soft effects probed. No new effects appear (beyond Kuhn & Rodrigo).

  Almeida, Sterman, Wogelsang '08
  Ahrens, Ferroglia, Neubert, Pecjak, Yang `11
  Manohar, Trott '12
  Skands, Webber, Winter '12

- ✓ The above result is very significant. It suggested that no large higher order corrections should be expected which made the discrepancy much more significant and appealing.

- ✓ F.O. EW effects checked. ~25% effect: not as small as one might naively expect!

  Hollik, Pagani '11
  Bernreuther, Si '12

- ✓ BLM/PMC scales setting does the job? Claimed near agreement with the measurements.

  Brodsky, Wu '12

- ✓ Higher order hard QCD corrections? The rest of this talk.

- ✓ Final state non-factorizable interactions? Unlikely.

  Mitov, Sterman '12
  Rosner '12

# NNLO QCD corrections to $A_{FB}$

# Intermezzo

- We have huge effort ongoing for the calculation of

  - Fully differential top pair production at NNLO
  - Everything is included – no approximations!
  - Stable top quarks only. Down the road include top decay.
  - For the moment we compute only pre-decided binned distributions.
  - Cannot store events for subsequent analyses. (on *To Do* list)
  - Calculations are very expensive and take long time. It is not easy at all to redo a calculation to change it "a little bit". Of course we will make the effort if the need is there.

  - For the moment we compute simultaneously with several fixed scales $mu_R$, $mu_F$ =(1/2,1,2)*$M_{top}$. Dynamical scales in the future.

  - Use mostly MSTW2008, but we also have everything computed also with NNPDF, CT10 and HERA.

  - Calculations for now only for Tevatron; LHC in progress.
  - Any energy can be done – matter of CPU!
  - $M_{top}$=173.3 GeV only. If top mass dependence is needed separate calculations will have to be done. CPU constrained. Perhaps compute for 3 $M_{top}$ values that are 1 GeV apart and use them to approximate in a narrow window. Good enough?

# NNLO QCD corrections to $A_{FB}$

✓ Computed AFB following the definition and binning of CDF '12

- Inclusive
- $|\Delta y|$
- $M_{tt}$
- $P_{T,tt}$

$$A_{FB} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\,, \quad \text{where} \quad \sigma^{\pm} \equiv \int \theta(\pm\Delta y)\, d\sigma$$

✓ The EW corrections to inclusive $A_{FB}$ included (from Bernreuther, Si '12)

$$\begin{aligned} A_{FB} &\equiv \frac{N_{ew} + \alpha_S^3 N_3 + \kappa\alpha_S^4 N_4}{\alpha_S^2 D_2 + \alpha_S^3 D_3 + \kappa\alpha_S^4 D_4} \\ &= \alpha_S \frac{N_3}{D_2} + \kappa\alpha_S^2 \left(\frac{N_4}{D_2} - \frac{N_3}{D_2}\frac{D_3}{D_2}\right) + \mathcal{O}(\alpha_S^3) \\ &\quad + \frac{N_{ew}}{\alpha_S^2 D_2}\left(1 - \kappa\frac{\alpha_S D_3}{D_2}\right). \end{aligned}$$

Two alternative expansions

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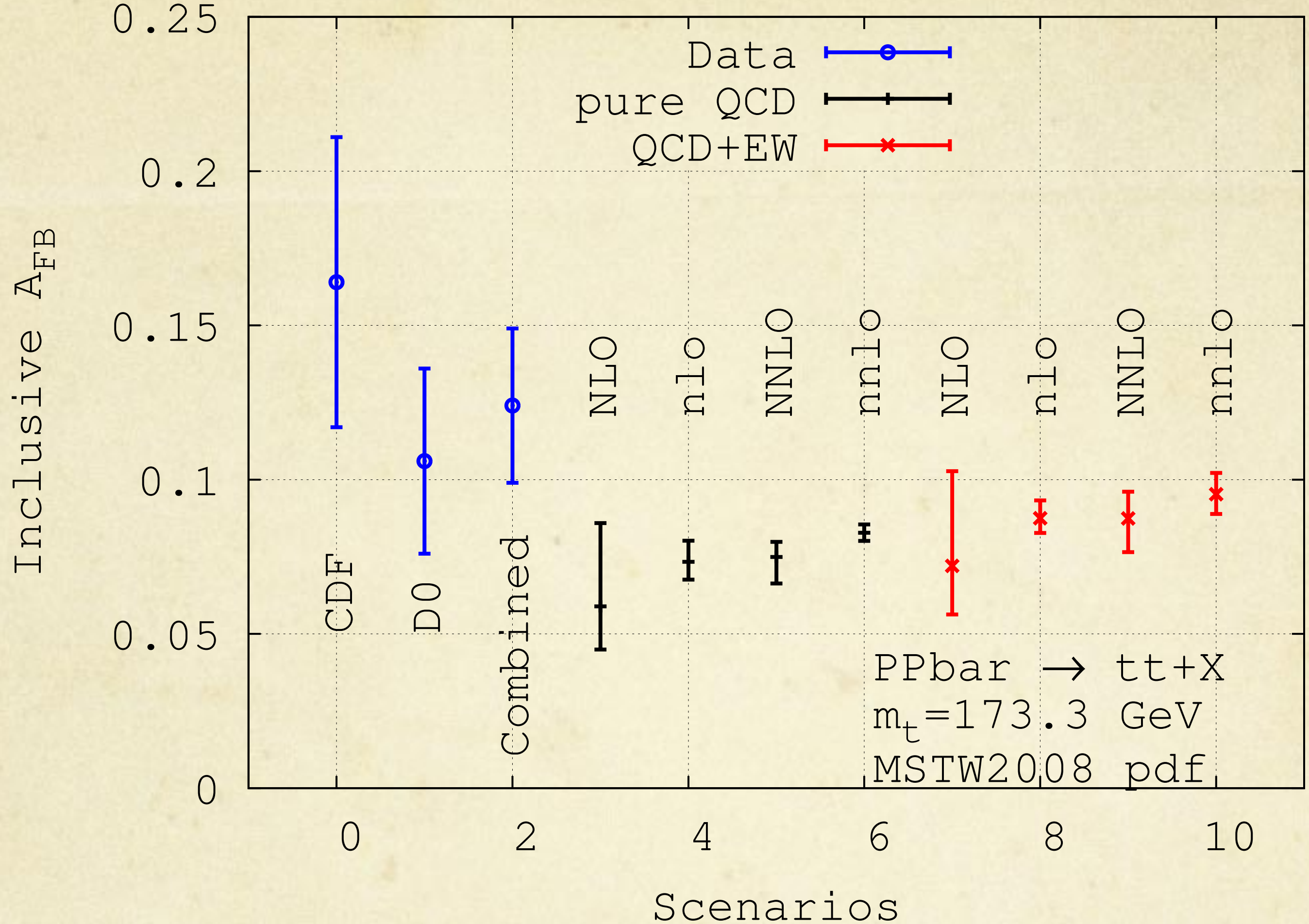
# NNLO QCD corrections to $A_{FB}$

- ✓ Checks and quality of the results
  - ✓ Pole cancellation: in each bin, for each scale.
  - ✓ MC errors (from integration) are a big worry due to large cancellation in $A_{FB}$
  - ✓ We have managed to make them negligible.
  - ✓ MC error in each bin is:
    - Few permil for differential distributions
    - Below 1% for AFB in each bin; with only highest Mtt bin with 1.5%
  - ✓ MC error on inclusive AFB is few permil.
  - ✓ Agreement with $\text{sigma}_{TOT}$ (Top++) to better than 0.5 permil (each scale)
  - ✓ Clearly, the numerical precision of the results is very high.
  - ✓ AT NLO QCD we agree with MCFM and Bernreuther & Si.
  - ✓ Another check at NNLO: consistent with $P_{T,tT}$ spectrum from ttj @ NLO
  - ✓ Computed for generic independent $\mu_F$ and $\mu_R$ (again, non-dynamic = $M_{top}$)

# Results for inclusive $A_{FB}$

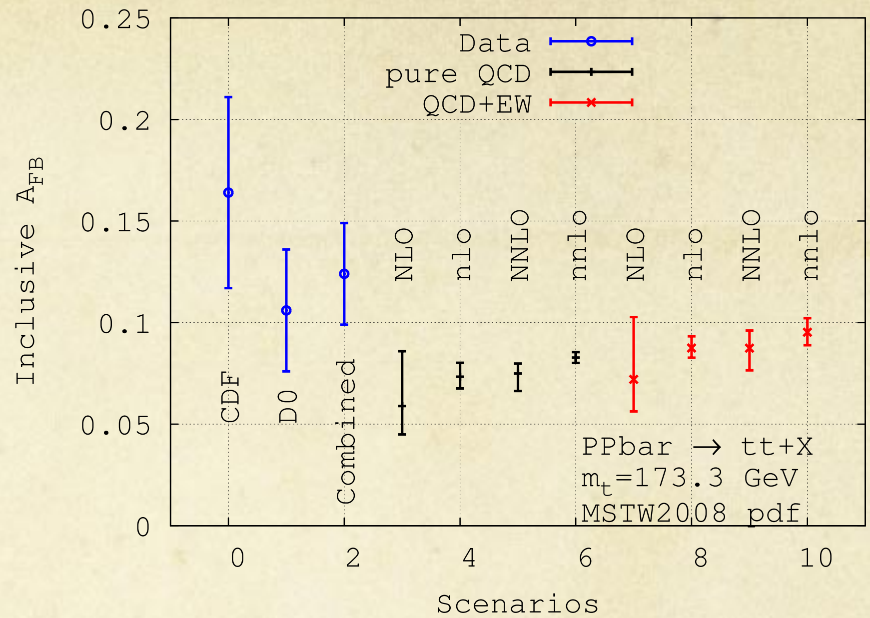



Errors due to scale variation only

How to read the above plot:

- *NLO, NNLO* : exact numerator and denominator (see previous slide)
- *nlo, nnlo* : expanded in powers of $a_S$

# Results for inclusive $A_{FB}$




- *NLO, NNLO* : exact numerator and denominator
- *nlo, nnlo* : expanded in powers of $a_S$

✓ We find large QCD corrections: NNLO ~ 27% of NLO (recall EW is 25% of NLO).

➔ This was not expected, given soft-gluon resummation suggests negligible correction.

✓ Adding all corrections $A_{FB}$ ~ 10%.

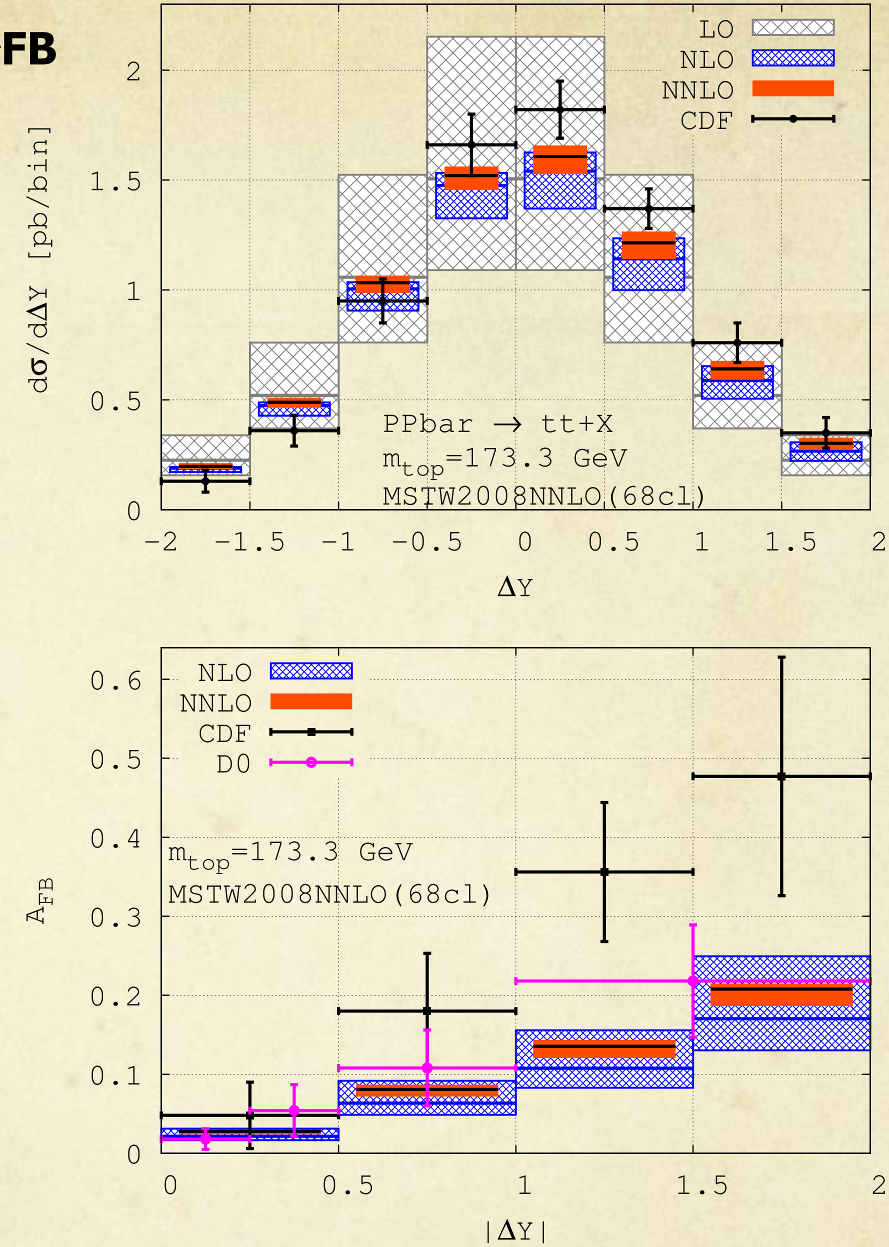
- ✓ Agrees with D0 and CDF/D0 naive combination
- ✓ Less than 1.5σ below CDF

✓ We consider this as *agreement* between SM and experiment.

✓ We observe good perturbative convergence (based on errors from scale variation)

✓ Expanded results (both *nlo* and *nnlo*) seem to have accidentally small scale variation

# Rapidity dependence of $A_{FB}$

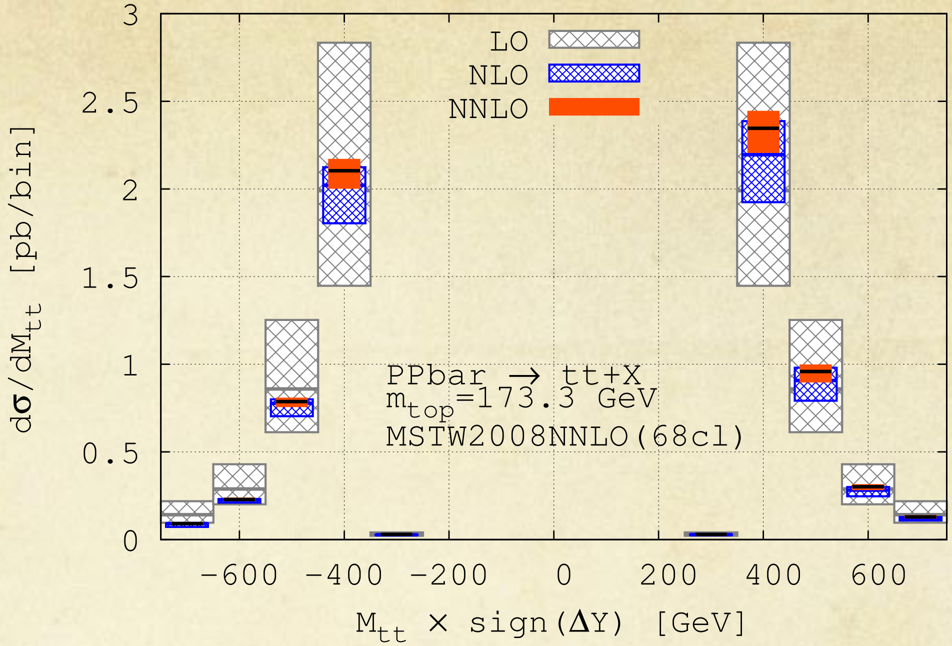



Errors due to scale variation only
- Pdf error small
- MC error negligible

- Perfect agreement with D0
- No agreement for $A_{FB}$ with CDF
- But differential x-section reasonably close to CDF …

FIG. 2: The $|\Delta y|$ differential distribution (top) and asymmetry (bottom) in pure QCD at LO (grey), NLO (blue) and NNLO (orange) versus CDF [2] and D0 [1] data. Error bands are from scale variation only. For improved readability some bins are plotted slightly narrower. The highest bins contain overflow events.

# $M_{tt}$ dependence of $A_{FB}$

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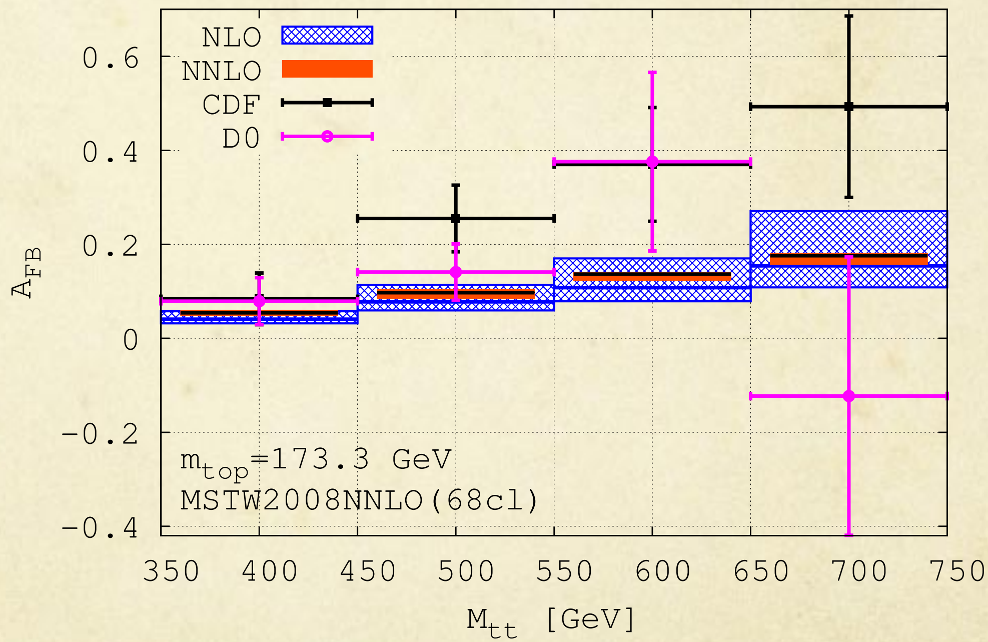



FIG. 3: As in fig. 2 but for the $M_{t\bar{t}}$ differential asymmetry. Both lowest and highest bins contain overflow events.

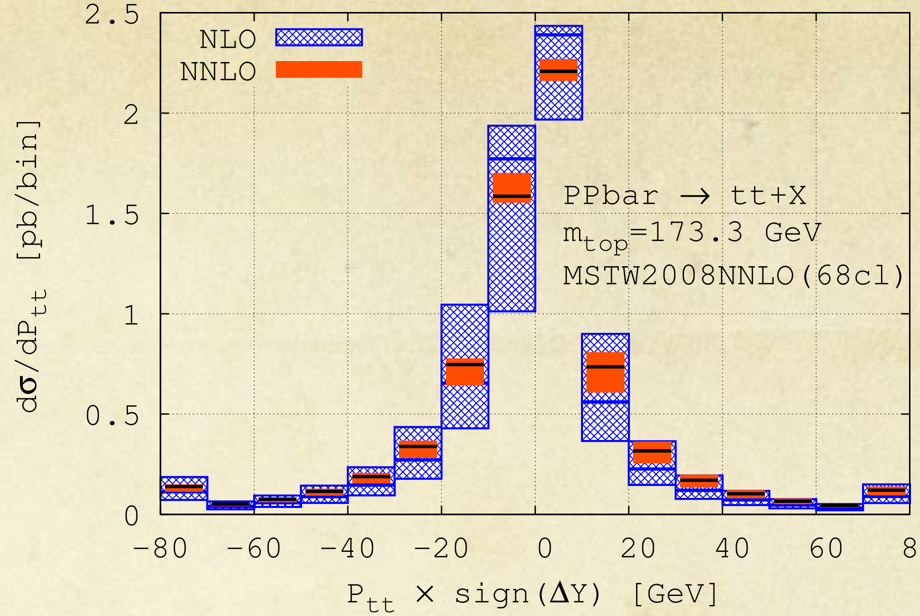
- Agreement with D0
- So-so agreement for $A_{FB}$ with CDF

# $P_{T,tt}$ dependence of $A_{FB}$

Errors due to scale variation only
- Pdf error small
- MC error in $A_{FB}$ 1%, i.e. small

- Note the change in shape in diff x-section
- No data to compare to…
- Difference NNLO-NLO is constant like as noted already by CDF
- The NNLO/NLO correction agrees with the preferred color-octet structure of the AFB discrepancy found in

Gripaios, Papaefstathiou, Webber '13



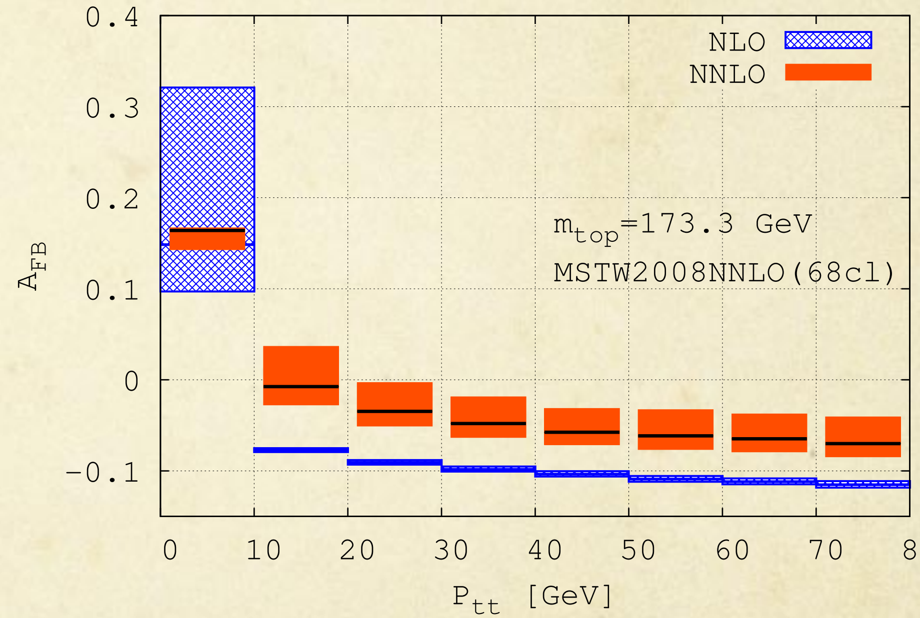
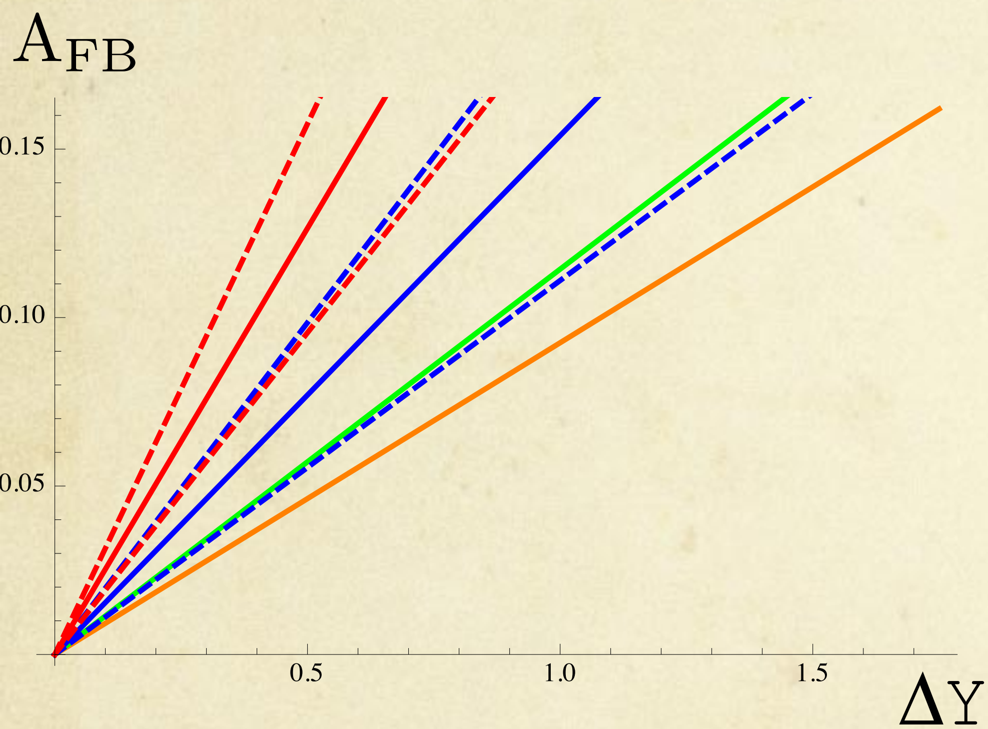
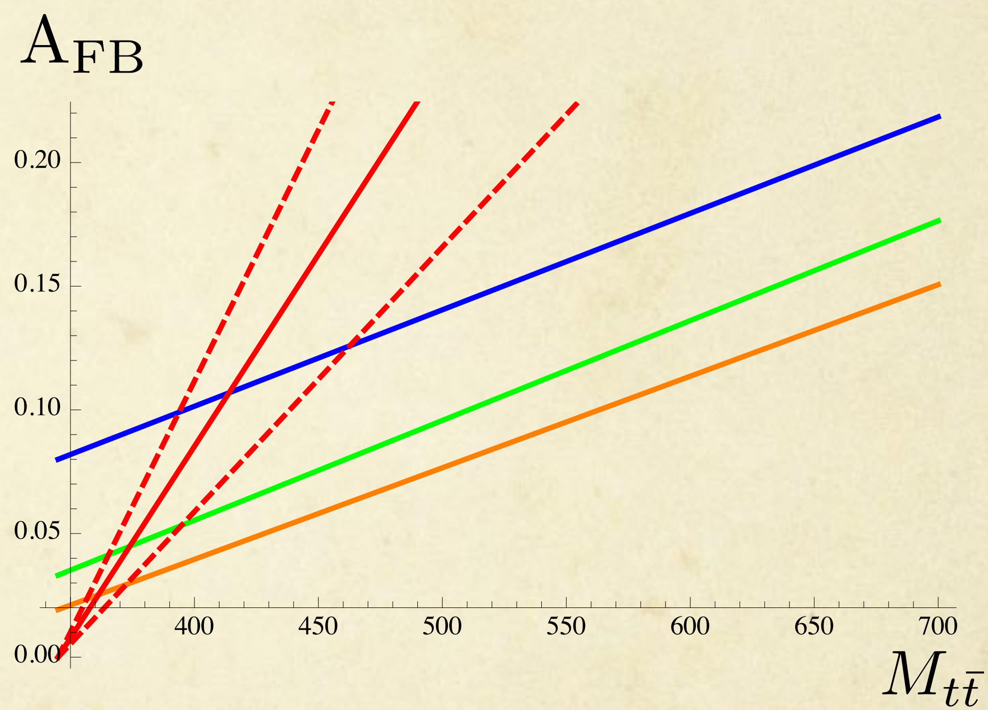




FIG. 4: The $P_{T,t\bar{t}}$ differential asymmetry in pure QCD at NLO (blue) and NNLO (orange). Error bands are from scale variation only. For improved readability some bins are plotted slightly narrower. The highest bins contain overflow events.

# The slope of $A_{FB}$

- It was noted previously that the differential asymmetry is close to a straight line
- For the rapidity dependence it is clear it is actually slightly curved at both NLO and NNLO
- For $M_{tt}$ at NNLO is very close to a straight line – unlike NLO




- CDF (dashes – errors)
- D0 (dashes – errors)
- NNLO
- NLO

- Agreement with D0 within errors even without EW corrections
- CDF is far off

# Understanding the origin of NNLO $A_{FB}$

- The anatomy of $A_{FB}$ at NNLO is similar to that at NLO but more extreme
  - Example: the contributions to the NNLO inclusive numerator

| | Factorization | RR | RV | VV |
|---|---|---|---|---|
| (princ. contr.)/$(\alpha_S^4 N_4)$ | $-0.47$ | 5.34 | $-3.90$ | 0.03 |

TABLE I: Sizes of the various principle contributions to the numerator of the inclusive $A_{FB}$ at NNLO in pure QCD. The size of the numerator is given in table II.

  - Driven by large cancellation between RR and RV
  - Sizable Factorization
  - Tiny VV

- Contributions from partonic reactions is similar to NLO:
  - Inclusive numerator is 99% qqbar
  - qg = qqbar/10^2
  - qq'=qqbar/10^4

In line with the contributions of these reaction to the total inclusive x-section

# The difference w/r to approximate NNLO

- Large difference for the inclusive asymmetry and numerator (no comparison for differential)

$$A_{FB}^{(NNLO)}/A_{FB}^{(NLO)} \text{ is } 1.27\ (1.13)$$ For unexpaned (expanded) definition

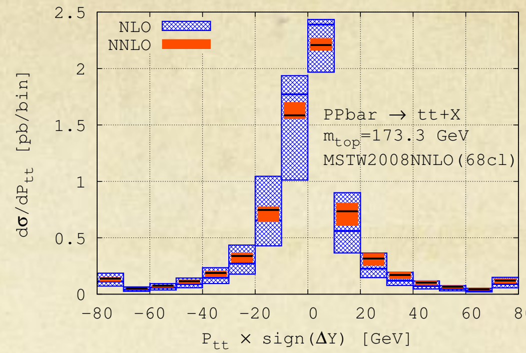
$Num_{NNLO}/Num_{NLO} = 1.34$

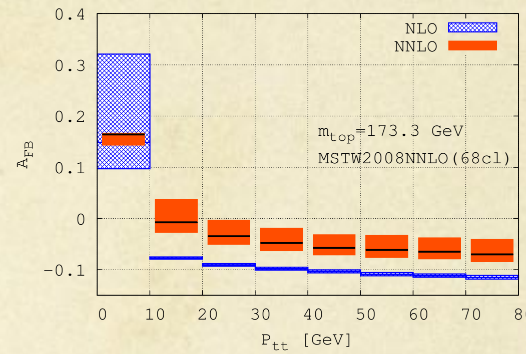
| | NLO | NNLO | NLO+NNLL |
|---|---|---|---|
| $\alpha_S^3 N_3 + \alpha_S^4 N_4$ [pb] | $0.394^{+0.211}_{-0.127}$ | $0.525^{+0.055}_{-0.085}$ | $0.448^{+0.080}_{-0.071}$ |
| $\alpha_S^4 N_4$ [pb] | – | 0.148 | – |
| $A_{FB}$[%] (eq. (3)) | $7.34^{+0.68}_{-0.58}$ | $8.28^{+0.27}_{-0.26}$ | $7.24^{+1.04}_{-0.67}$ |
| $A_{FB}$[%] (eq. (2)) | $5.89^{+2.70}_{-1.40}$ | $7.49^{+0.49}_{-0.86}$ | – |

TABLE II: Comparison of the numerator in eq. (2) and the inclusive asymmetry $A_{FB}$ computed in pure QCD at NLO (with NLO pdf set), NNLO and NLO+NNLL [20]. Only errors from $\mu_F = \mu_R$ scale variation are shown.

- To better understand this look at the $P_{T,tt}$ differential asymmetry

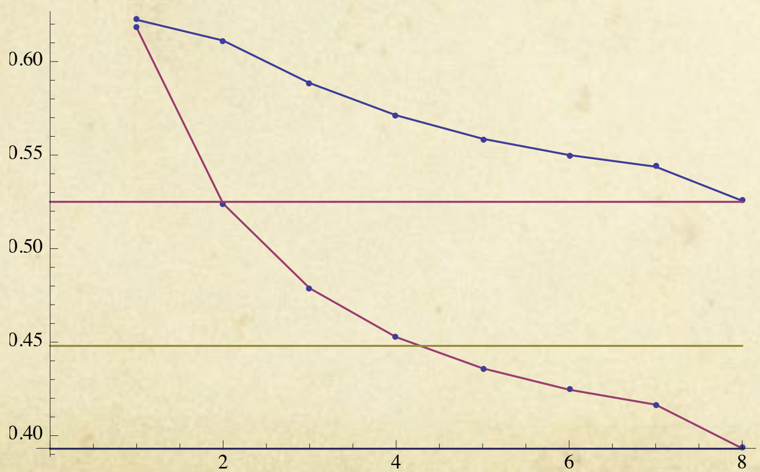
# The difference w/r to approximate NNLO



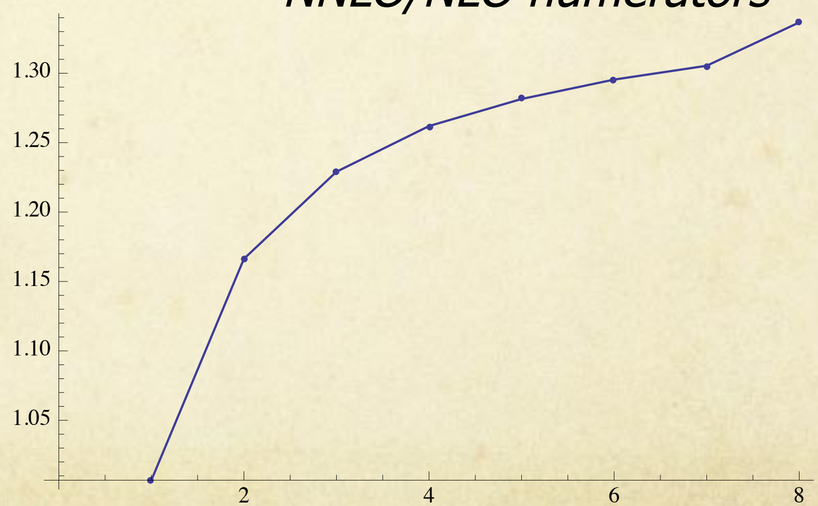

- It is better to look at the Cumulative differential asymmetry (i.e. the inclusive asymmetry with a cut on $P_{T,tt}$)
- Recall: the inclusive asymmetry is <u>not</u> an integral over the differential one …
- Soft gluon resummation "operates" near $P_{T,tt}$=0. The Cumulative asymmetry will illustrate how $A_{FB}$ develops
- Cumulative $P_{T,tt}$ asymmetry:

*NNLO and NLO numerators*



$P_{T,tt}$ bin

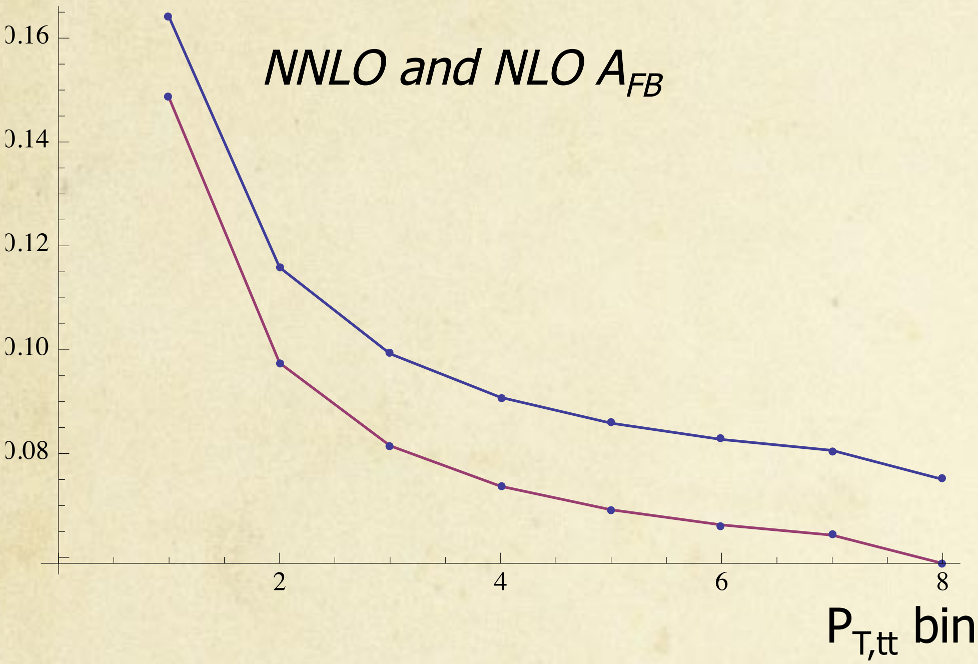
*NNLO/NLO numerators*

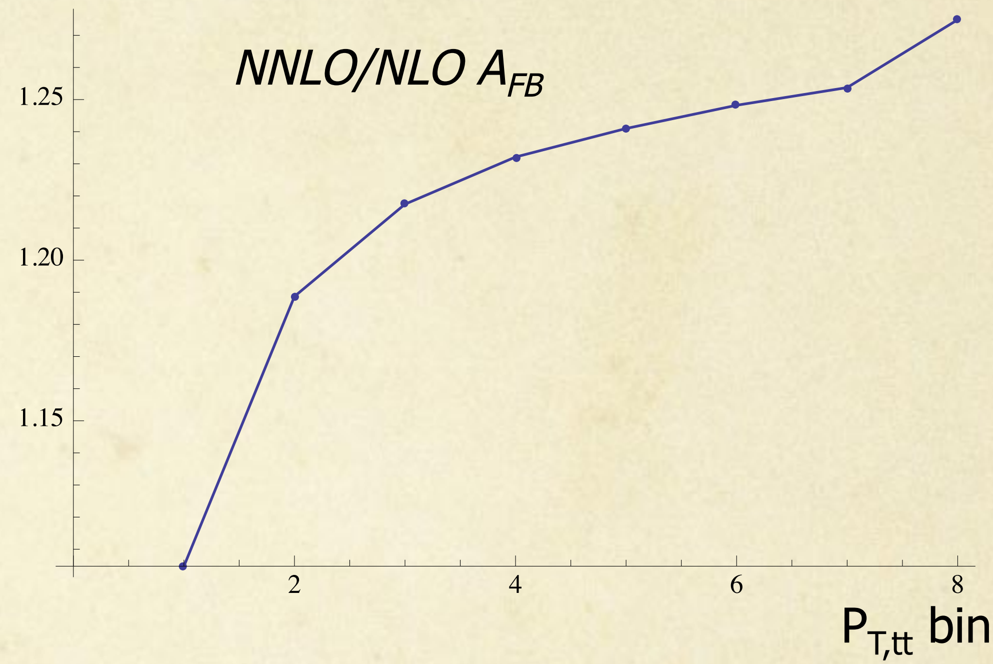


$P_{T,tt}$ bin

# The difference w/r to approximate NNLO

- Cumulative $P_{T,tt}$ asymmetry:




- Equal NLO and NNLO numerators in the first bin (where soft resummation is most relevant)
- Thus, the NLO – NNLO difference in the first bin is only due to the denominator!
- They start to diverge fast afterwards
- The second bin contains already 50% of the NNLO-NLO difference in the numerator

- Clearly the difference between NLO and NNLO comes from hard emissions which cannot be described by soft-gluon resummation

Top quark mass

# Why the top mass?

✓ Knowing the top mass has important implications beyond immediate collider physics

- ✓ Higgs inflation
- ✓ Vacuum stability in SM and beyond
- ✓ …

✓ How well do we know the top mass?

- ➢ $m_{top}$ is not an observable; cannot be measured directly.
- ➢ It is extracted indirectly, through the sensitivity of observables to $m_{top}$

$$\sigma^{\rm exp}(\{Q\}) = \sigma^{\rm th}(m_t, \{Q\})$$

- ✓ The implication: the "determined" value of $m_{top}$ is as sensitive to theoretical modeling as it is to the measurement itself

✓ The measured mass is close to the pole mass (top decays …)

✓ Lots of activity (past and ongoing). A big up-to-date review:

Juste, Mantry, Mitov, Penin, Skands, Varnes, Vos, Wimpenny '13

The message I'd like to convey: the problem is not "academic"

Example: look at the spread across current measurements

- Current World Average: $m_{top}$= 173.34±0.76 GeV arXiv:1403.4427
- New CMS (l+j): $m_{top}$= 172.04 ± 0.19 (stat.+JSF) ± 0.75 (syst.) GeV. TOP-14-001

✓ Comparable uncertainties; rather different central values!

- This is possible in the context of my discussion: different theory systematics.

To me, the problem of $m_{top}$ extraction should turn from "more precise determination" to better understanding of the theory systematics and their size.

In order to properly understand and estimate the theory systematics we propose a particular observable

Frixione, Mitov '14

$$pp \to t\bar{t} + X$$

$$t \to W + b + X$$

$$W \to \ell + \nu_\ell$$

These are ttbar dilepton events, subject to standard cuts:

$$|\eta_\ell| \leq 2.4 \ , \ |\eta_b| \leq 2.4 \ ,$$

$$p_{T,\ell} \geq 20 \text{ GeV} \ , \ p_{T,b} \geq 30 \text{ GeV}$$

- Construct the distributions from leptons only
- Require b-jets [anti-$k_T$, R=0.5] within the detector (i.e. integrate over the b's)

The definition of the observable possesses several important properties:

- It is inclusive of hadronic radiation, which makes it well-defined to all perturbative orders in the strong coupling,
- It does not require the reconstruction of the $t$ and/or $\bar{t}$ quarks (indeed we do not even speak of $t$ quark),
- Due to its inclusiveness, the observable is as little sensitive as possible to modelling of hadronic radiation. This feature increases the reliability of the theoretical calculations.

✓ The top mass is extracted from the ***shapes, not normalizations***, of the following distributions:

| kinematic distribution |
| --- |
| $p_T(\ell^+)$ |
| $p_T(\ell^+\ell^-)$ |
| $M(\ell^+\ell^-)$ |
| $E(\ell^+) + E(\ell^-)$ ← Studied before by: Biswas, Melnikov, Schulze '10 |
| $p_T(\ell^+) + p_T(\ell^-)$ |

✓ Working with distributions directly is cumbersome.

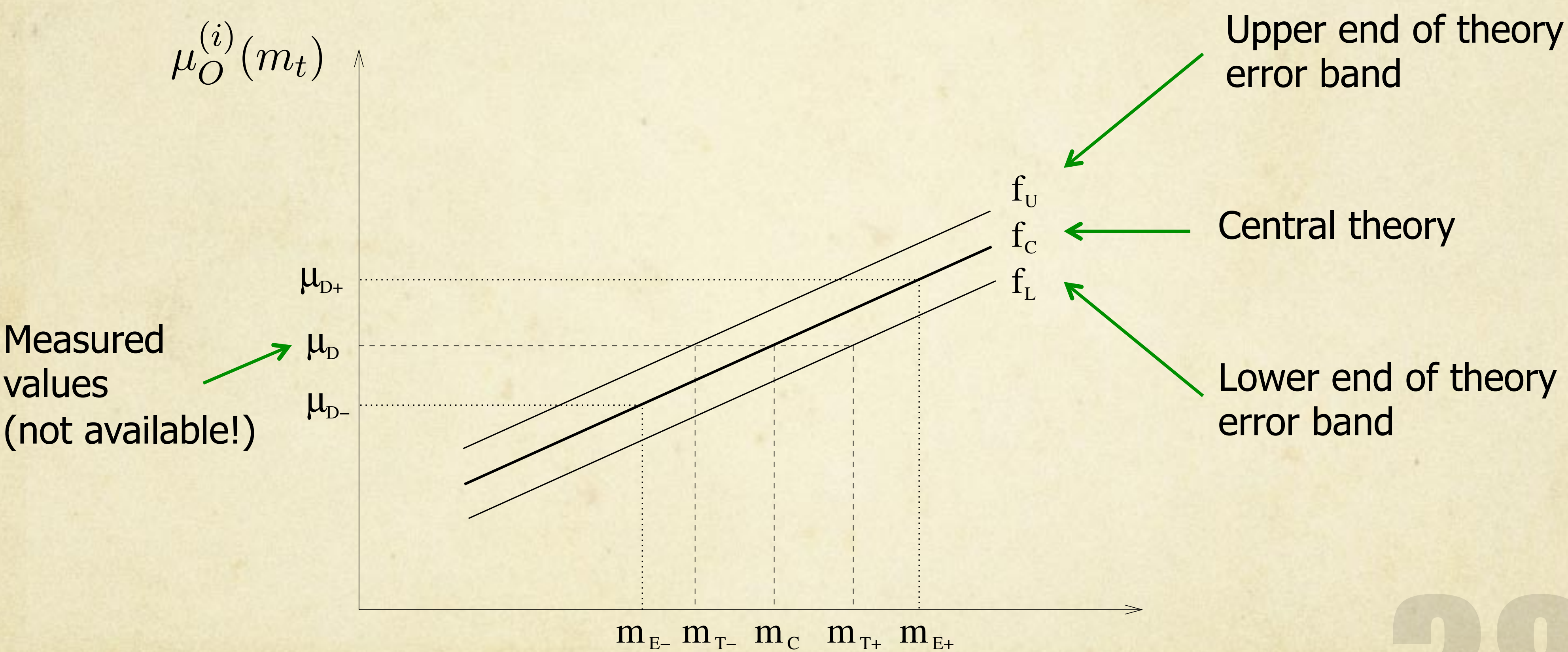
✓ Instead, utilize the first 4 moments of each distribution

$$\sigma = \int d\sigma \qquad \mu_O^{(i)} = \frac{1}{\sigma}\int d\sigma\, O^{\,i} \qquad \mu_O^{(0)} = 1\,, \qquad \mu_O^{(1)} = \langle O \rangle$$

Note: both are subject to cuts (or no cuts); we tried both.

- Here is how it all works:

1) Compute the dependence of the moments $\mu_O^{(i)}(m_t)$ on the top mass
2) Measure the moment
3) Invert 1) and 2) to get the top mass (would be the pole mass, since this is what we use)

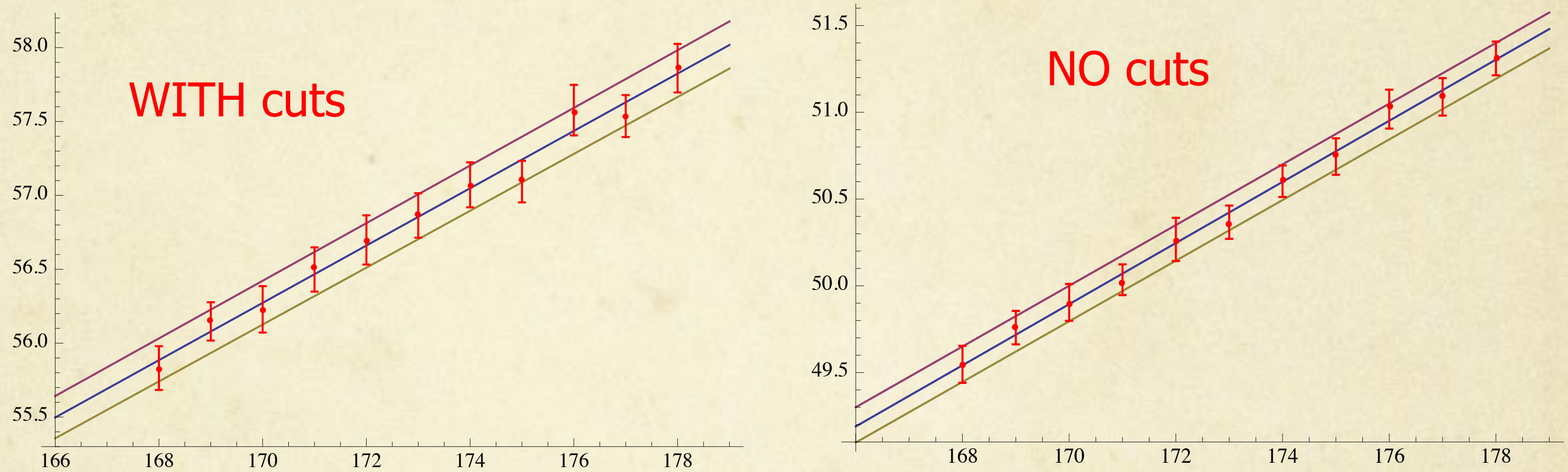


How to compute the theory error band for $\mu_O^{(i)}(m_t)$ ?

- Compute $\mu_O^{(i)}(m_t)$ for a finite number of $m_t$ values: $m_t = (168, 169, \ldots, 178)$ GeV

  Then get best straight line fit (works well in this range).

Example:
- Single lepton $P_T$
- Subject to cuts




✓ Errors: pdf and scale variation; restricted independent variation

$$0.5 \le \xi_F, \xi_R \le 2 \qquad \xi_{F,R} = \mu_{F,R}/\hat{\mu} \text{ and } \hat{\mu} \text{ is a reference scale}$$

✓ There are statistical fluctuation (from MC even generation) No issue for lower moments 1M events; 30% pass the cuts.

## Theory systematics

- We access them by computing the observables in many different ways.
- For a fair (albeit biased) comparison across setups and moments we use pseudodata (PD) generated by us
- Compare the systematics by comparing the top mass "extracted" by each setup from PD.

6 Setups:

| label | fixer order accuracy | parton shower/fixed order | spin correlations |
|---|---|---|---|
| 1 | LO | PS | - |
| 2 | LO | PS | MS |
| 3 | NLO | PS | - |
| 4 | NLO | PS | MS |
| 5 | NLO | FO | - |
| 6 | LO | FO | - |

3 F,R Scales:

$$\hat{\mu}^{(1)} = \frac{1}{2}\sum_i m_{T,i} \ , \ i \in (t,\bar{t}) \, ,$$

$$\hat{\mu}^{(2)} = \frac{1}{2}\sum_i m_{T,i} \ , \ i \in \text{ final state} \, ,$$

$$\hat{\mu}^{(3)} = m_t \, ,$$

All is computed with aMC@NLO (with Herwig)

# Theory systematics: impact of shower effects

| obs. | $m_t^{(3)} - m_t^{(5)}$ | $m_t^{(3)} - m_t^{\mathrm{pd}}$ | $m_t^{(1)} - m_t^{(6)}$ | $m_t^{(1)} - m_t^{\mathrm{p}}$ |
|---|---|---|---|---|
| 1 | $-0.35^{+1.14}_{-1.16}$ | $+0.12$ | $-2.17^{+1.50}_{-1.80}$ | $-0.67$ |
| 2 | $-4.74^{+1.98}_{-3.10}$ | $+11.14$ | $-9.09^{+0.76}_{-0.71}$ | $+14.19$ |
| 3 | $+1.52^{+2.03}_{-1.80}$ | $-8.61$ | $+3.79^{+3.30}_{-4.02}$ | $-6.43$ |
| 4 | $+0.15^{+2.81}_{-2.91}$ | $-0.23$ | $-1.79^{+3.08}_{-3.75}$ | $-1.47$ |
| 5 | $-0.30^{+1.09}_{-1.21}$ | $+0.03$ | $-2.13^{+1.51}_{-1.81}$ | $-0.67$ |

NLO LO

| label | kinematic distribution |
|---|---|
| 1 | $p_T(\ell^+)$ |
| 2 | $p_T(\ell^+\ell^-)$ |
| 3 | $M(\ell^+\ell^-)$ |
| 4 | $E(\ell^+) + E(\ell^-)$ |
| 5 | $p_T(\ell^+) + p_T(\ell^-)$ |

| label | fixer order accuracy | parton shower/fixed order | spin correlations |
|---|---|---|---|
| 1 | LO | PS | - |
| 2 | LO | PS | MS |
| 3 | NLO | PS | - |
| 4 | NLO | PS | MS |
| 5 | NLO | FO | - |
| 6 | LO | FO | - |

- Setups 2,3 are anomalous (More later).
- Clearly big impact of NLO corrections (shower matters more at LO).

NOTE: proper PS study would require Pythia etc. Not done here.

# Theory systematics: impact of NLO vs LO effects

| obs. | $m_t^{(4)} - m_t^{(2)}$ | $m_t^{(4)} - m_t^{\rm pd}$ | $m_t^{(3)} - m_t^{(1)}$ | $m_t^{(3)} - m_t^{\rm pd}$ | $m_t^{(5)} - m_t^{(6)}$ | $m_t^{(5)} - m_t^{\rm pd}$ |
|---|---|---|---|---|---|---|
| 1 | $+1.16^{+1.43}_{-1.60}$ | $+0.41$ | $+0.79^{+1.43}_{-1.60}$ | $+0.12$ | $-1.03^{+1.22}_{-1.43}$ | $+0.47$ |
| 2 | $-2.79^{+1.27}_{-1.65}$ | $-1.18$ | $-3.05^{+1.35}_{-1.64}$ | $+11.14$ | $-7.41^{+1.64}_{-2.72}$ | $+15.87$ |
| 3 | $-0.73^{+3.21}_{-3.45}$ | $+0.84$ | $-2.18^{+3.03}_{-3.30}$ | $-8.61$ | $+0.09^{+2.42}_{-2.91}$ | $-10.13$ |
| 4 | $+1.74^{+3.27}_{-3.78}$ | $+0.16$ | $+1.23^{+3.10}_{-3.61}$ | $-0.23$ | $-0.70^{+2.79}_{-3.09}$ | $-0.38$ |
| 5 | $+0.99^{+1.42}_{-1.72}$ | $+0.25$ | $+0.70^{+1.40}_{-1.72}$ | $+0.03$ | $-1.13^{+1.23}_{-1.33}$ | $+0.33$ |

PS+MS

PS

-

| label | kinematic distribution |
|---|---|
| 1 | $p_T(\ell^+)$ |
| 2 | $p_T(\ell^+\ell^-)$ |
| 3 | $M(\ell^+\ell^-)$ |
| 4 | $E(\ell^+) + E(\ell^-)$ |
| 5 | $p_T(\ell^+) + p_T(\ell^-)$ |

| label | fixer order accuracy | parton shower/fixed order | spin correlations |
|---|---|---|---|
| 1 | LO | PS | - |
| 2 | LO | PS | MS |
| 3 | NLO | PS | - |
| 4 | NLO | PS | MS |
| 5 | NLO | FO | - |
| 6 | LO | FO | - |

- Setups 2,3 are anomalous (More later).
- Clearly big impact of NLO corrections.

# Theory systematics: impact of Spin-Correlations effects

| obs. | $m_t^{(4)} - m_t^{(3)}$ | $m_t^{(4)} - m_t^{\rm pd}$ | $m_t^{(2)} - m_t^{(1)}$ | $m_t^{(2)} - m_t^{\rm pd}$ |
|---|---|---|---|---|
| 1 | $+0.29^{+1.17}_{-1.14}$ | $+0.41$ | $-0.08^{+1.66}_{-1.96}$ | $-0.75$ |
| 2 | $-12.32^{+1.62}_{-2.13}$ | $-1.18$ | $-12.58^{+0.90}_{-0.94}$ | $+1.60$ |
| 3 | $+9.45^{+2.36}_{-2.16}$ | $+0.84$ | $+8.00^{+3.74}_{-4.26}$ | $+1.57$ |
| 4 | $+0.39^{+2.93}_{-3.16}$ | $+0.16$ | $-0.11^{+3.42}_{-4.16}$ | $-1.58$ |
| 5 | $+0.22^{+1.12}_{-1.28}$ | $+0.25$ | $-0.06^{+1.65}_{-2.07}$ | $-0.73$ |

NLO+PS

LO+PS

| label | kinematic distribution |
|---|---|
| 1 | $p_T(\ell^+)$ |
| 2 | $p_T(\ell^+\ell^-)$ |
| 3 | $M(\ell^+\ell^-)$ |
| 4 | $E(\ell^+) + E(\ell^-)$ |
| 5 | $p_T(\ell^+) + p_T(\ell^-)$ |

| label | fixer order accuracy | parton shower/fixed order | spin correlations |
|---|---|---|---|
| 1 | LO | PS | - |
| 2 | LO | PS | MS |
| 3 | NLO | PS | - |
| 4 | NLO | PS | MS |
| 5 | NLO | FO | - |
| 6 | LO | FO | - |

- NOTE setups 2,3 Huge dependence on spin correlations
- NLO corrections make a difference.

# "Best" Theory Predictions (NLO+PS+MS): choice of scale and Moment

$m_t^{\mathrm{pd}} = 174.32\ \mathrm{GeV}$

[...] = $\chi^2$ per d.o.f.

$$\hat{\mu}^{(1)} = \frac{1}{2}\sum_i m_{T,i}\ ,\ i \in (t,\bar{t})\,,$$
$$\hat{\mu}^{(2)} = \frac{1}{2}\sum_i m_{T,i}\ ,\ i \in\ \text{final state}\,,$$
$$\hat{\mu}^{(3)} = m_t\,,$$

All 5 observables NLO+PS+MS

| scale | $i=1$ | $i=1\oplus 2$ | $i=1\oplus 2\oplus 3$ |
|---|---|---|---|
| 1 | $174.48^{+0.73}_{-0.77}[5.0]$ | $174.55^{+0.72}_{-0.76}[5.0]$ | $174.56^{+0.71}_{-0.76}[5.1]$ |
| 2 | $174.73^{+0.77}_{-0.80}[4.3]$ | $174.74^{+0.76}_{-0.79}[4.3]$ | $174.91^{+0.75}_{-0.79}[4.1]$ |
| 3 | $172.54^{+1.03}_{-1.07}[1.6]$ | $172.46^{+0.99}_{-1.05}[1.6]$ | $172.22^{+0.95}_{-1.04}[1.4]$ |
| $1\oplus 2\oplus 3$ | $174.16^{+0.81}_{-0.85}$ | $174.17^{+0.80}_{-0.84}$ | $174.17^{+0.78}_{-0.84}$ |

| label | kinematic distribution |
|---|---|
| 1 | $p_T(\ell^+)$ |
| 2 | $p_T(\ell^+\ell^-)$ |
| 3 | $M(\ell^+\ell^-)$ |
| 4 | $E(\ell^+)+E(\ell^-)$ |
| 5 | $p_T(\ell^+)+p_T(\ell^-)$ |

Observables 1,4,5 NLO+PS+MS

| scale | $i=1$ | $i=1\oplus 2$ | $i=1\oplus 2\oplus 3$ |
|---|---|---|---|
| 1 | $174.67^{+0.75}_{-0.77}[3.0]$ | $174.67^{+0.75}_{-0.77}[3.0]$ | $174.61^{+0.74}_{-0.77}[3.2]$ |
| 2 | $174.81^{+0.83}_{-0.80}[6.2]$ | $174.80^{+0.82}_{-0.80}[6.2]$ | $174.85^{+0.82}_{-0.80}[6.1]$ |
| 3 | $172.63^{+1.85}_{-1.16}[0.2]$ | $172.64^{+1.82}_{-1.15}[0.2]$ | $172.58^{+1.81}_{-1.15}[0.2]$ |
| $1\oplus 2\oplus 3$ | $174.44^{+0.92}_{-0.87}$ | $174.44^{+0.92}_{-0.87}$ | $174.43^{+0.91}_{-0.87}$ |

Observable 1 NLO+PS+MS

| scale | $i=1$ | $i=1\oplus 2$ | $i=1\oplus 2\oplus 3$ |
|---|---|---|---|
| 1 | $174.73^{+0.80}_{-0.79}[0.2]$ | $174.73^{+0.80}_{-0.79}[0.2]$ | $174.72^{+0.80}_{-0.79}[0.2]$ |
| 2 | $174.78^{+0.90}_{-0.90}[0.6]$ | $174.78^{+0.90}_{-0.90}[0.6]$ | $174.78^{+0.90}_{-0.90}[0.6]$ |
| 3 | $172.73^{+2.0}_{-1.2}[0.5]$ | $172.73^{+1.96}_{-1.19}[0.5]$ | $172.73^{+1.96}_{-1.19}[0.5]$ |
| $1\oplus 2\oplus 3$ | $174.46^{+0.99}_{-0.92}$ | $174.46^{+0.99}_{-0.92}$ | $174.45^{+0.99}_{-0.92}$ |

# Theory systematics: Predictions

| observable; setup | $i = 1$ | $i = 1 \oplus 2$ | $i = 1 \oplus 2 \oplus 3$ |
|---|---|---|---|
| all; LO+PS | $187.90^{+0.6}_{-0.6}[428.3]$ | $187.71^{+0.60}_{-0.60}[424.2]$ | $187.83^{+0.58}_{-0.60}[442.8]$ |
| all; LO+PS+MS | $175.98^{+0.63}_{-0.69}[16.9]$ | $176.05^{+0.63}_{-0.68}[17.8]$ | $176.12^{+0.61}_{-0.68}[18.9]$ |
| all; NLO+PS | $175.43^{+0.74}_{-0.80}[29.2]$ | $176.20^{+0.73}_{-0.79}[30.1]$ | $175.67^{+0.73}_{-0.76}[31.2]$ |
| all; $\mathrm{NLO_{FO}}$ | $174.41^{+0.72}_{-0.73}[96.6]$ | $174.82^{+0.71}_{-0.73}[93.1]$ | $175.44^{+0.70}_{-0.68}[94.8]$ |
| all; $\mathrm{LO_{FO}}$ | $197.31^{+0.42}_{-0.35}[2496.1]$ | $197.19^{+0.42}_{-0.35}[2505.6]$ | $197.48^{+0.36}_{-0.35}[3005.6]$ |
| 1,4,5; LO+PS | $173.68^{+1.08}_{-1.31}[0.8]$ | $173.68^{+1.08}_{-1.31}[0.9]$ | $173.75^{+1.08}_{-1.31}[0.9]$ |
| 1,4,5; LO+PS+MS | $173.61^{+1.10}_{-1.34}[1.0]$ | $173.63^{+1.10}_{-1.34}[1.0]$ | $173.62^{+1.10}_{-1.34}[1.0]$ |
| 1,4,5; NLO+PS | $174.40^{+0.75}_{-0.81}[3.5]$ | $174.43^{+0.75}_{-0.81}[3.5]$ | $174.60^{+0.75}_{-0.79}[3.2]$ |
| 1,4,5; $\mathrm{NLO_{FO}}$ | $174.73^{+0.72}_{-0.74}[5.5]$ | $174.72^{+0.71}_{-0.74}[5.6]$ | $175.18^{+0.64}_{-0.71}[4.6]$ |
| 1,4,5; $\mathrm{LO_{FO}}$ | $175.84^{+0.90}_{-1.05}[1.2]$ | $175.75^{+0.89}_{-1.05}[1.2]$ | $175.82^{+0.89}_{-1.04}[1.2]$ |

$$m_t^{\mathrm{pd}} = 174.32\ \mathrm{GeV}$$

[...] = $\chi^2$ per d.o.f.

| label | kinematic distribution |
|---|---|
| 1 | $p_T(\ell^+)$ |
| 2 | $p_T(\ell^+\ell^-)$ |
| 3 | $M(\ell^+\ell^-)$ |
| 4 | $E(\ell^+) + E(\ell^-)$ |
| 5 | $p_T(\ell^+) + p_T(\ell^-)$ |

# Conclusions on top mass

- ✓ New developments have resurrected the interest in knowing $m_{top}$ precisely
  - ✓ Vacuum Stability in SM
  - ✓ Higgs Inflation
- ✓ There are many dedicated hadron collider measurements.
  They return consistent values around $m_{top}$ = 173 GeV
  and uncertainty (mostly on the measurement!) of below 1 GeV.
- ✓ Questions remain: can there be a significant additional theoretical systematics O(1 GeV) ?
- ✓ This is not an abstract problem: $m_{top}$ is not an observable and so is a theoretically defined concept.
- ✓ Proposed an approach, with emphasis on control over theory systematics.
  - NLO vs LO: O(1 GeV);
  - Shower effects much smaller at NLO than at LO.
  - Spin correlations crucial, but depend on the observable.
  - Awaiting the measurement: O(100k) events exist!
  - Adding higher moments is not a game changer
  - Unlikely to be able to use the data to tell which scale choice is 'right'.
  - Future improvements, notably NNLO, will likely also play an important role.
  - In some cases the differences are so big that the measurements will easily tell us which way of computing things is right and which is not!

Expectations for future developments in ttbar production

&

list of current bottlenecks

✓ So far discussed past and current status. What about the future prospects?

- Fully differential partonic MC for top pair production in NNLO QCD
- Fully differential NNLO partonic MC with top decay in NWA. Top decay already known through NNLO:

Gao, Li, Zhu '12
Brucherseifer, Caola, Melnikov '13

- The next big milestone is to shower NNLO top production.
  - Initially by using existing LL showers
  - Will add a momentum in the direction of extending showers to NLL and beyond
  - NNLO+PS is still a fairly new subject with first results for processes with simpler analytical structure (like H, Z).

Hamilton, Nason, Re, Zanderighi '13
Hoeche, Li, Prestel '14
Karlberg, Re, Zanderighi '14

  - Extending showers to top production will require a general solution. Some activity:

Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13

✓ What about current bottlenecks?

- NLO ttbar calculations are now extremely advanced.
- At NNLO the clear bottleneck is the fast evaluation of one-loop amplitudes for RV corrections to inclusive ttbar.
- Going farther into the future, if we want to have ttbar+jet etc also at NNLO we will need to develop ways of computing the required 2-loop amplitudes. This is a totally open problem at present.

# Summary and Conclusions

- Top physics is in precision phase
- Total x-section for tT production now known in full NNLO
- Fully differential top production to appear soon. This will become standard for LHC run 2.
- Important phenomenology
  - Constrain and improve PDF's
  - Searches for new physics
  - Very high-precision test of SM (given exp is already at 5% !). Good agreement.

# New results

- New results for NNLO QCD corrections to $A_{FB}$
- Large corrections found. (NNLO ~ 27% NLO)
- QCD + EW corrections bring $A_{FB}$ ~ 10%, in agreement with D0 and near-agreement with CDF
- Full differential results for Tevatron/LHC expected soon (finalizing paper).